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Editor's Note: Copies of the colored map appearing in the paper by Gregory and Williams in the present issue may be obtained from the Society. The maps are unfolded and will be mailed in tubes. Orders accompanied by remittance (25 cents per copy) should be sent to The Geological Society of America, 419 West 117 Street, New York, N. Y., *Attention:* Miss Osborne

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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STATISTICAL RELATION BETWEEN TiO_2, Fe_2O_3, AND FeO IN ROCKS AND ORES DURING DIFFERENTIATION OF A TITANIFEROUS MAGMA

BY PIERRE EVRARD

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ABSTRACT

This paper presents the results of a statistical study of the relations that hold between Ti and Fe during the process of magmatic differentiation in the anorthositic and gabbroic series of rocks and ores of the Adirondacks. It is shown that in the course of differentiation for each series the total number of molecules of TiO_2, FeO, and Fe_2O_3 as a whole and of the number of TiO_2 molecules have increased continually. A simple mathematical expression is derived which expresses the manner of variation of TiO_2 relative to $TiO_2 + Fe_2O_3 + FeO$.

PRELIMINARY NOTES

This paper presents the results of a statistical study of the relations that bind Fe and Ti during the process of magmatic differentiation in an eruptive body and in the associated titaniferous ores.

Any geochemical problem is too complex, it requires the collaboration of too many different sciences and specialists, to allow one student to treat it by himself. To proceed safely and quickly these investigations must be carried on by a combination

of workers. Therefore, I think I may publish this study although it refers to one "magmatic province" only—*i.e.*, the Adirondack province.

I want to offer now, for criticism, the method I have used. The actual problem of the metallogeny of deposits involves passing beyond the purely descriptive stage to arrive at an explanation. The answer to the often-asked question "Why is ore where it is?" must include a relative measure of quantity. What are the conditions favorable to the occurrence of an ore body of a definite type, and how are they to be measured?

For orthomagmatic ore bodies, the comparison seems to be easier between eruptive rocks and the deposits derived from them. On the other hand, metalliferous masses and eruptive rocks constitute a whole, which cannot be separated if one wants to characterize the initial magma.

A "magmatic province" is defined both by its minerals and by the eruptive rocks from which are born the ores, since the occurrence of all is ruled by differentiation in its broadest meaning.

It is well known that the titaniferous iron ores, chromites, platinum, etc., are derived from the differentiation of basic eruptives. The phenomenon is here either a crystallization differentiation with accumulation, or an injection of residual fluids.[1]

I had an opportunity, in a preceding paper (1944), rapidly to review the various hypotheses proposed to explain the details of the process itself. The main conclusion, upon which most authors now agree, is the late character of the deposition for titaniferous iron ores, contrary to the classification upheld by Rosenbusch about the iron oxides in general.

Thanks to Professor Buddington's (1939) remarkable work on the Adirondack igneous rocks and their metamorphism, I could, from afar, study the important Adirondack petrologic province and the magmatic titaniferous iron ores that occur in it. I used in the largest measure this big synthesis.

SOME GEOLOGICAL CHARACTERS OF THE ADIRONDACKS

I shall briefly sketch the geological characters of the Adirondacks, after the summary given at the beginning of Buddington's work. The region is situated in northern New York south of the St. Lawrence River and between Lake Champlain on the east and Lake Ontario on the west.[2]

I shall confine my studies to the oldest eruptive series: important masses of anorthosites and gabbros with which the titaniferous deposits are related.

Professor Buddington distinguished:

A. The most ancient rocks of this region which belong to the Grenville series (sedimentary materials strongly metamorphosed): crystalline schist, gneiss, marbles, quartzites, skarn, etc.

B. I. The anorthositic series which represents the first widely developed intrusions. One can observe, locally, series with a similar order and composition: anorthosite, an orthositic gabbro, very mafic gabbros, apatite-rich gabbros with ilmenite-mag-

[1] Osborne (1928) is an advocate of this last hypothesis concerning the ores of the Adirondacks.

[2] *See* a map in Buddington (1939) or in Balk (1931).

netite. The segregations occur in concordant sheets and also in dikes. All the rocks of these series belong to the "saturated" type. In the main mass there are primary zoning and flowage structures, particularly in the border facies. The primary magma that produced the anorthositic complex is supposed to have had the composition of a gabbroic anorthosite.

II. Then come the basic gabbros, formerly considered younger than the syenite-granite series and now described as younger than the anorthositic rocks but older than the syenite-granite complexes. These gabbros intrude the Grenville series and anorthosites; they also occur in concordant sheets. Their composition is that of an olivine gabbro. They are "undersaturated." They occur throughout the Adirondack Mountains, but their mass is much less important than that of the anorthositic rocks and the younger quartz syenites and granites. In metagabbro masses adjacent to anorthositic bodies, there are bands of mafic metagabbro, sometimes very rich in ilmenite-magnetite.

III. Still younger is a series of dioritic rocks (Rossie series) found in intrusive sills or laccoliths; they are younger than the gabbros and older than the syenitic complex.

C. The next magmatic age is characterized by the intrusion of a magma that probably had the composition of a pyroxene-quartz syenite.

This brief review shows the relationships of the two magmatic series upon which are based my investigations: (I) the *saturated anorthositic* series, and (II) the *undersatured basic gabbros;* both gave rise to ilmenite-magnetite deposits.

CHOICE OF A DIAGRAM FOR THE INTERPRETATION

My purpose is to find a quantitative relation between the oxides TiO_2, and Fe_2O_3, present in rocks and titaniferous iron ores which originated in the differentiation of one magma.

Within the rocks these oxides represent only a small percentage of the total constituents ;they occur in the transparent as well as in the opaque minerals. In the ores, they are largely predominant.

A progressive passage is often observed from a titanium-poor rock to a titanium-rich one, and then to an ore. The solution of the problem must explain the whole series of variations for the three oxides studied through all the stages of differentiation.

One must use absolute molecular quantities (per weight units), and consequently it is indispensable to develop a method different from the ternary diagrams. In fact, these record relative variations only. In a ternary diagram, rock and ore may be represented by the same point provided they have the same ratio of TiO_2:Fe_2O_3:FeO. However, between rock and ore, the absolute amounts vary from few units to several hundreds of mols per volume unit. It would be utterly impossible to use arithmetic or linear scales in cartesian co-ordinates. Moreover, when one studies the variation dx of the variable term x (for instance a concentration variation with respect to a sum of concentrations), one is bound to choose logarithmic scales. The mode of association of the oxides is not taken into account.

The diagram to be used is then characterized by: (1) the total number of mols; $TiO_2 + Fe_2O_3 + FeO$, in the weight unit of rock, for instance 100 kg, along the

abscissa, (2) the absolute number of TiO_2 mols. contained in the weight unit of rock (100 kg.) in ordinate, (3) choosing logarithmic scales for the co-ordinates.

The possible variation in space of a representative point is limited in the diagram plan:

(1) by a line inclined at 45° and passing through the co-ordinate point (1,1). This line represents the case of no Fe_2O_3 and no FeO. Its equation is:

$$N_{TiO_2} = N_{TiO_2+O+O'}$$

(2) by some points that can be easily computed. They correspond to the following cases: 100% TiO_2 in the ore: 100% $FeO \cdot TiO_2$; 99.92% FeO or 99.92% $FeO \cdot Fe_2O_3$ and 0.08% TiO_2 (one mol. of TiO_2).[4]

TABLE 1.—*Co-ordinate values*

Limit compositions	N_{TiO_2}	$N_{TiO_2+Fe_2O_3+FeO}$
100% TiO_2	1250	1250
100% $TiO_2 \cdot FeO$	667	1334
0.08% TiO_2 and 99.92% FeO	1	1388
0.08% TiO_2 and 99.92% $FeO \cdot Fe_2O_3$	1	861

All these hypotheses are reported in Table 1, which gives the co-ordinate values of these points.

The limit points can be joined by very flat curves, and I have actually drawn straight lines. (*See* Figure 2, dashed line.)

The dashed line 100% $TiO_2 \cdot FeO$ to 100% $FeO \cdot Fe_2O_3$ is an artificial limit for it implies the assumption that no mineral contains either FeO or Fe_2O_3 in excess, for instance in solid solution, with respect to the above mineralogical formula. However I shall use it.

The diagram was simplified by the fact that I did not have to take into account TiO_2 mol numbers lower than 1 and values lower than 10 for the total $N_{TiO_2+Fe_2O_3+FeO}$. These cases represented only fractions of per cents in analyses.

RESULTS OF PLOTTING

In accordance with foregoing conditions, I have indicated the results of plotting 75 analyses (Nos. 50 to 124) of rocks and minerals (Fig. 1) belonging to the saturated and undersaturated groups.

A rapid observation shows an average linear and fairly regular distribution of the points. But the exact direction of the "most probable line" to be chosen for a simple and approximate representation of the relations between N_{TiO_2} and $N_{TiO_2+Fe_2O_3+FeO}$ would require probability computations and the application of the mean square

[3] I represent the number of TiO_2 mols in the weight unit by N_{TiO_2}. The meaning of $N_{TiO_2+Fe_2O_3+FeO}$ is easily understood.

[4] It is not possible to represent the case of 0% TiO_2, because the point would be at $-\infty$ upon a logarithmic diagram.

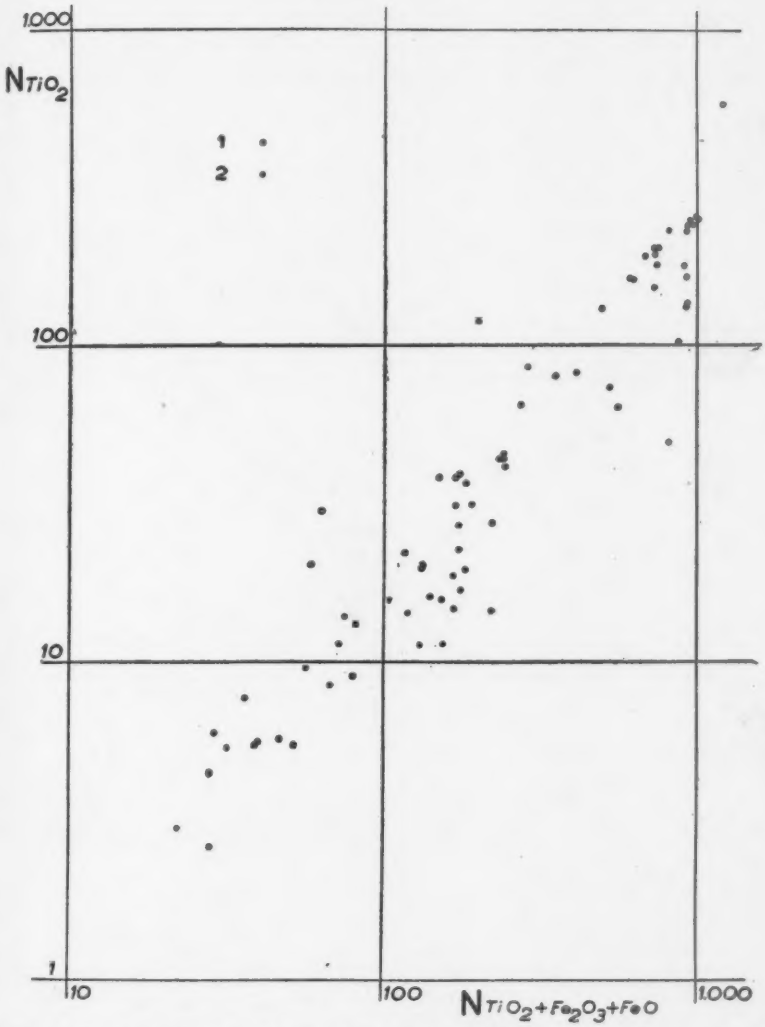

FIGURE 1.—*Number of molecules of TiO_2 plotted on logarithmic scale against number of molecules of TiO_2 + Fe_2O_3 + FeO in rocks and ores of the "saturated" anorthositic series and "undersaturated" gabbroic series of the Adirondacks*

theory. This would necessitate long calculations which are not justified in a problem that is only a first step in this question.

On the other hand, it is reasonable and easier (1) to distinguish between the rocks belonging to each magma, the saturated one and the undersaturated one; (2) to group the analyses according to the types of rocks; (3) to take into account the average values only.

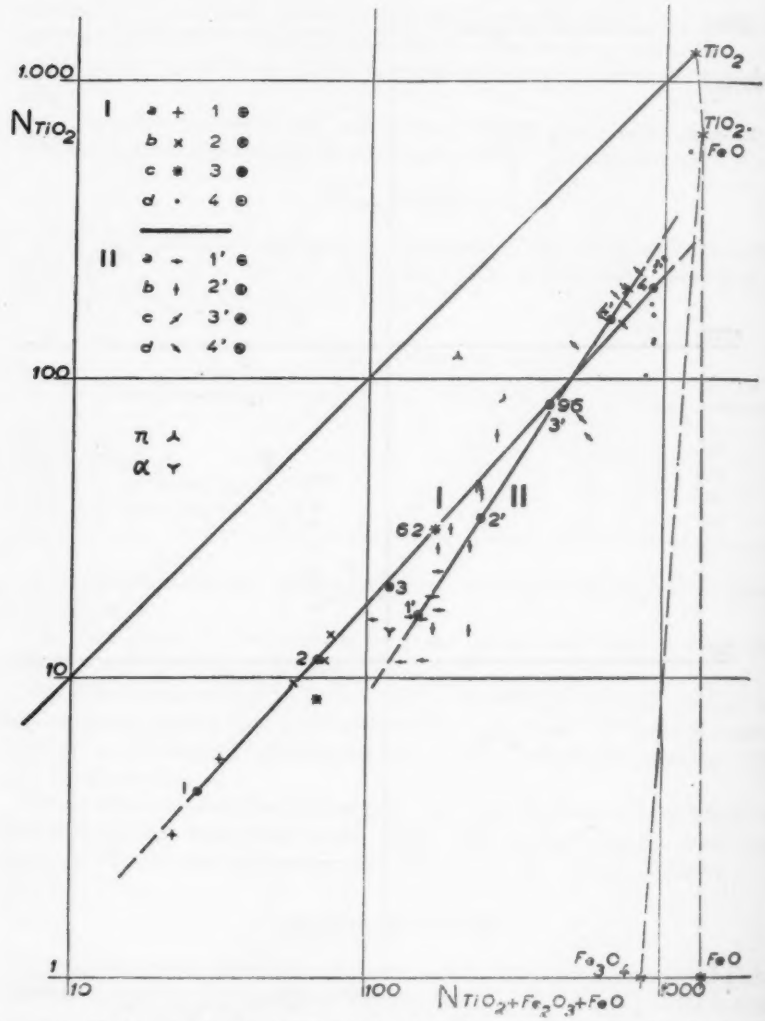

FIGURE 2.—*Number of molecules of TiO_2 plotted on logarithmic scale against number of molecules of $TiO_2 + Fe_2O_3$ for rock types (based on average of a number of analyses) of the "saturated" anorthositic series and "undersaturated" gabbroic series of the Adirondacks*

The location of the individual analyses averaged are also shown.

This method yielded better-characterized conclusions (Fig. 2).[5]

The first group (I. saturated rocks) includes: (a) analyses 57 and 58 (B-16 and B-17). Both are of rocks from the *central anorthositic mass*. The first one (57) is the

[5] To consult tables of analyses and lists of references, *see* the end of this chapter.

average analysis of 60 samples selected in the mass, powdered, and analyzed together; the second one (58) was made on the powder of 40 specimens gathered in different places in the same massive.

(b) the analyses of the *anorthositic border facies*. I proceeded in the same way: I took the average values of the analyses nos. 59, 60, and 61 (B-18, -19, -20). Each analysis was already the result of mixing, after powdering, of 10, 75 and 55 samples, respectively, selected in the border zone;

(c) the late differentiation facies with gabbroic features. They were represented in my documentation by the analyses nos. 62, 63 (B-24, -25); no. 62 is a norite in layers, cutting the anorthosite border facies; no. 63 is an anorthositic gabbro cutting the central facies.[6]

(d) the results of 14 analyses published in Kemp's work (1899) on the titaniferous ores of the Adirondacks. These ores come from the region of Sanford Lake, from Millpond Pit (66-K and 112-K to 115-K), and from Cheney Pit (118-K to 124-K); they are genetically related to the first differentiated series. Unluckily, these analyses only give TiO_2 and total Fe percentages. Consequently I calculated the number of FeO mols necessary to saturate the number of TiO_2 mols and then turned the remaining Fe into $FeO \cdot Fe_2O_3$.

The four average points 1, 2, 3, 4 (arithmetic average) (Fig. 2) are practically on a straight line.[7] A similar result is obtained with the second group formed by the undersaturated rocks called by Buddington basic metamorphic gabbros or metagabbros.

This differentiated series includes:

(a) metagabbros in the Northwestern Adirondacks, (1) in the zone of the Grenville rocks (79–81; B-50–52)

(2) in the granite zone; here occur amphibolites, metagabbros, and diabases (82–86; B-55–59). The average of all these analyses is fixed on the diagram by the point 1′ (Fig. 2).

(b) metagabbros in the Eastern Adirondacks. They are related to the ores of the Split Rock Mine type. There are nine analyses of gabbro masses or gneisses, metagabbros, granulites (with pyroxene, garnets, and andesine), and wall rocks of the ores (87–95:B-60–68).

The average of these is the point 2′ (Fig. 2).

(c) a mafic metagabbro with 30 per cent opaque elements.

---

[6] It is at present impossible to take into the average analyses 63 and 64, of pegmatitic facies which are not common and in which the TiO_2 content is abnormal (Osborne, 1928). Moreover, their importance in volume is slight, and TiO_2 combines with calcium and silica to produce sphene.

Consequently their locations deviate a good deal from the normal averages (Fig. 2, point A).

A similar case is met with in analysis 67 (Fig. 2, point γ) of a gabbro, the mafic character of which is due to assimilation phenomena.

However, I thought it useful to plot the values of these analyses, though they are not taken into account in the average. These particular cases will be looked at later, when the problem limited to its magmatic phenomena will be cleared up a little more. It is to be noted that the pegmatitic facies have values higher than the average, while the assimilation facies has, on the contrary, lower values.

[7] The norite (62) is a rock of frequent occurrence and characteristic of differentiations with which titaniferous deposits are related (for instance Norway, Bushveld, Ural). Its point is exactly on the line joining the central and border anorthosites to the average of the ores (Fig. 2).

TABLE 2.—*List of analyses*

No.	Reference	Percentages			Molecular Numbers (×1000)			
		TiO_2	Fe_2O_3	FeO	TiO_2	Fe_2O_3	FeO	Total
57	B.-16	0.43	0.75	1.59	5.38	4.69	22.10	32.17
58	B.-17	0.24	0.35	1.24	3.00	2.19	17.25	22.44
1 = I.a.: Average					4.19			27.30
59	B.-18	1.12	1.31	3.89	14.–	8.20	54.–	76.20
60	B.-19	0.77	0.91	3.02	9.65	5.69	41.9	57.24
61	B.-20	0.92	0.66	4.17	11.50	4.13	57.9	73.53
2 = I.b.: Average					11.71			69.01
62	B.-24	2.54	1.69	9.27	31.8	10.60	129.–	171.4
63	B.-25	0.69	0.70	3.98	8.6	4.38	55.3	68.28
64	B.-26	9.65	1.40	5.32				
65	B.-27	6.88	1.59	14.12				
67	B.-30	1.15	1.35	7.00				
3 = I.c.: Average					20.2			119.85
		TiO_2	Fe total					
66	B.-28-L	13.38	59.56		167.–	300.–	467.–	934.–
112	Kemp (1899)	10.73	63.45		134.–	333.–	467.–	934.–
113		19.74	53.62		246.5	237.–	484.–	968.–
114		20.24	55.62		252.5	247.5	500.–	1000.–
115		20.49	54.80		256.–	242.–	498.–	996.–
116		8.25	62.15		103.–	336.–	439.–	878.–
117		15.77	40.33		197.–	175.–	372.–	744.–
118		10.91	62.65		136.–	328.–	464.–	928.–
119		20.03	51.22		250.–	222.–	472.–	944.–
120		19.52	51.30		244.–	225.–	469.–	938.–
121		18.70	51.44		234.–	229.–	463.–	926.–
122		14.52	56.60		181.5	277.–	458.5	917.–
123		4.–	62.66		50.–	357.–	407.–	814.–
124		47.50	36.86		593.–	22.–	615.–	1230.–
4 = I.d.: Average					203.–			910
		TiO_2	Fe_2O_3	FeO				
79	B.-50	1.31	3.44	7.35	16.4	21.5	102.1	140.–
80	B.-51	1.28	2.25	5.39	16.–	14.1	74.85	104.9
81	B.-52	1.53	6.14	8.01	19.2	38.4	111.2	168.8
82	B.-55	1.83	1.81	10.20	22.9	11.3	141.7	175.9
83	B.-56	1.28	1.08	9.40	16.–	6.75	130.5	153.25
84	B.-57	0.91	1.73	7.82	11.4	10.8	108.5	130.70
85	B.-58	1.37	1.93	10.69	17.1	12.1	148.5	177.7
86	B.-59	0.93	1.49	9.69	11.6	9.3	134.5	155.4
1′ = II.a: Average					16.3			151.1

TABLE 2—*Continued*

No.	Reference	Percentages			Molecular Numbers (×1000)			
		TiO_2	Fe_2O_3	FeO	TiO_2	Fe_2O_3	FeO	Total
87	B.-60-L	1.18	2.29	12.39	14.75	14.30	193.–	222.05
88	B.-61-L	2.54	2.17	10.60	31.80	13.60	147.3	192.7
89	B.-62	3.55	1.86	12.80	44.30	11.60	178.–	233.9
90	B.-63-L	1.20	1.39	10.45	15.–	8.70	145.–	168.7–
91	B.-64-L	3.37	1.61	13.81	42.1	10.07	192.–	244.17
92	B.-65-L	3.03	2.03	13.12	27.9	12.7	182.2	222.8
93	B.-66	2.22	1.73	9.79	27.8	10.8	136.–	174.6
94	B.-67	3.55	3.24	12.76	44.3	20.6	177.–	241.9
95	B.-68-L	5.26	4.63	12.99	65.7	29.–	180.5	275.2
2′ = II.b: Average					34.85			241.85
96	B.-69	7.43	6.60	19.80	93.–	41.2	275	409.2
3′ = II.c: Average					93.–			409.2
97	B.-70-L Kemp (1910)	5.21	30.34	22.81	65.–	190.–	303.–	558.–
98	B.-71-L Kemp (1910)	15.66	15.85	27.94	195.8	99.–	388.–	682.8
99	B.-72-L Kemp (1910)	16.45	20.35	28.82	206.–	127.–	400.–	733.–
100	B.-73-L Kemp (1910)	12.31	30.68	27.92	154.–	192.–	388.–	734.–
105		14.70	38.43	23.40	183.7	242.–	325.–	750.7
106		10.55	11.52	21.34	131.9	72.9	296.–	500.–
107		13.07	11.16	28.35	163.3	69.7	394.–	627.–
108	Kemp (1899)	13.15	23.77	21.24	164.4	148.5	295.–	607.9
109		6.01	34.13	17.33	75.2	213.5	240.7	529.4
110		16.37	30.36	25.46	264.5	189.7	354.–	748.2
111		18.82	26.30	29.78	235.2	164.4	413.5	813.1
4′ = II.d.: Average					161.6			662.1

57. (B.-16).—Analysis of composite grab sample of 60 fragments of Marcy anorthosite from 10 localities in core of St. Regis-Marcy unit along road from Algonquin (Saranac quadrangle) to half a mile NW. of Rustic Lodge (Long Lake quadrangle). Analyst, R. B. Ellestad.

58. (B.-17).—Analysis of composite grab sample of about 40 samples of Marcy anorthosite across 2-mile section of Jay sheet, from 1 mile NE. of Jay to 0.7 mile west of North Jay (Ausable quadrangle). A quite uniform coarse-grained rock with a narrow range of variation in composition. Analyst, R. W. Perlich.

59. (B.-18).—Composite grab sample of 10 specimens of Whiteface gabbroic anorthosite facies from 5 miles along the strike of northeast border of anorthosite between Lake Flower and North of McCauley Pond (Saranac quadrangle). None of the more mafic facies commonly present in the border facies happened to occur along the belt sampled. Analyst, R. B. Ellestad.

60. (B.-19).—Composite grab sample of fragments of Whiteface facies of gabbroic anorthosite from 75 localities in area NE. of Reber, between it and the belt of Grenville passing through Sugarloaf Mountain, Willsboro quadrangle. Represents about 2 miles across the foliation along two traverses, 1½ miles apart. The percentage of mafic minerals was variable. No relics of Grenville or evidences of assimilation were observed. Analyst, R. B. Ellestad.

61. (B-20).—Analysis of composite grab sample of about 55 fragments of Whiteface facies from section 2½ miles across strike SE. from Long Pond outlet to 1½ miles NW. of Willsboro (Willsboro quadrangle), and N. of the highway. Analyst, R. B. Ellestad.

62. (B.-24).—Norite, sharply defined band in anorthosite of border facies, 1⅛ miles W. of Gabriels (Saranac quadrangle). Analyst, R. W. Perlich.

abscissa, (2) the absolute number of TiO_2 mols. contained in the weight unit of rock (100 kg.) in ordinate, (3) choosing logarithmic scales for the co-ordinates.

The possible variation in space of a representative point is limited in the diagram plan:

(1) by a line inclined at 45° and passing through the co-ordinate point (1,1). This line represents the case of no Fe^2O^3 and no FeO. Its equation is:

$$N_{TiO_2} = N_{TiO_2+O+O^3}$$

(2) by some points that can be easily computed. They correspond to the following cases: 100% TiO_2 in the ore: 100% $FeO \cdot TiO_2$; 99.92% FeO or 99.92% $FeO \cdot Fe_2O_3$ and 0.08% TiO_2 (one mol. of TiO_2).[4]

TABLE 1.—*Co-ordinate values*

Limit compositions	N_{TiO_2}	$N_{TiO_2+Fe_2O_3+FeO}$
100% TiO_2	1250	1250
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All these hypotheses are reported in Table 1, which gives the co-ordinate values of these points.

The limit points can be joined by very flat curves, and I have actually drawn straight lines. (*See* Figure 2, dashed line.)

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RESULTS OF PLOTTING

In accordance with foregoing conditions, I have indicated the results of plotting 75 analyses (Nos. 50 to 124) of rocks and minerals (Fig. 1) belonging to the saturated and undersaturated groups.

A rapid observation shows an average linear and fairly regular distribution of the points. But the exact direction of the "most probable line" to be chosen for a simple and approximate representation of the relations between N_{TiO_2} and $N_{TiO_2+Fe_2O_3+FeO}$ would require probability computations and the application of the mean square

[3] I represent the number of TiO_2 mols in the weight unit by N_{TiO_2}. The meaning of $N_{TiO_2+Fe_2O_3+FeO}$ is easily understood.

[4] It is not possible to represent the case of 0% TiO_2, because the point would be at -00 upon a logarithmic diagram.

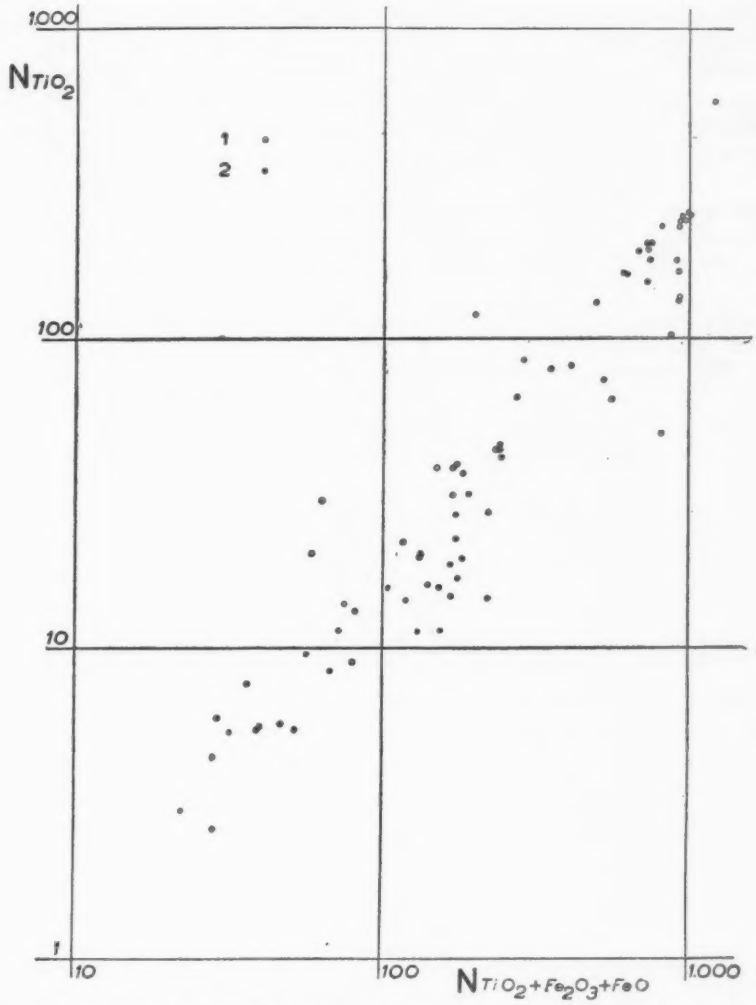

FIGURE 1.—*Number of molecules of TiO_2 plotted on logarithmic scale against number of molecules of TiO_2 + Fe_2O_3 + FeO in rocks and ores of the "saturated" anorthositic series and "undersaturated" gabbroic series of the Adirondacks*

theory. This would necessitate long calculations which are not justified in a problem that is only a first step in this question.

On the other hand, it is reasonable and easier (1) to distinguish between the rocks belonging to each magma, the saturated one and the undersaturated one; (2) to group the analyses according to the types of rocks; (3) to take into account the average values only.

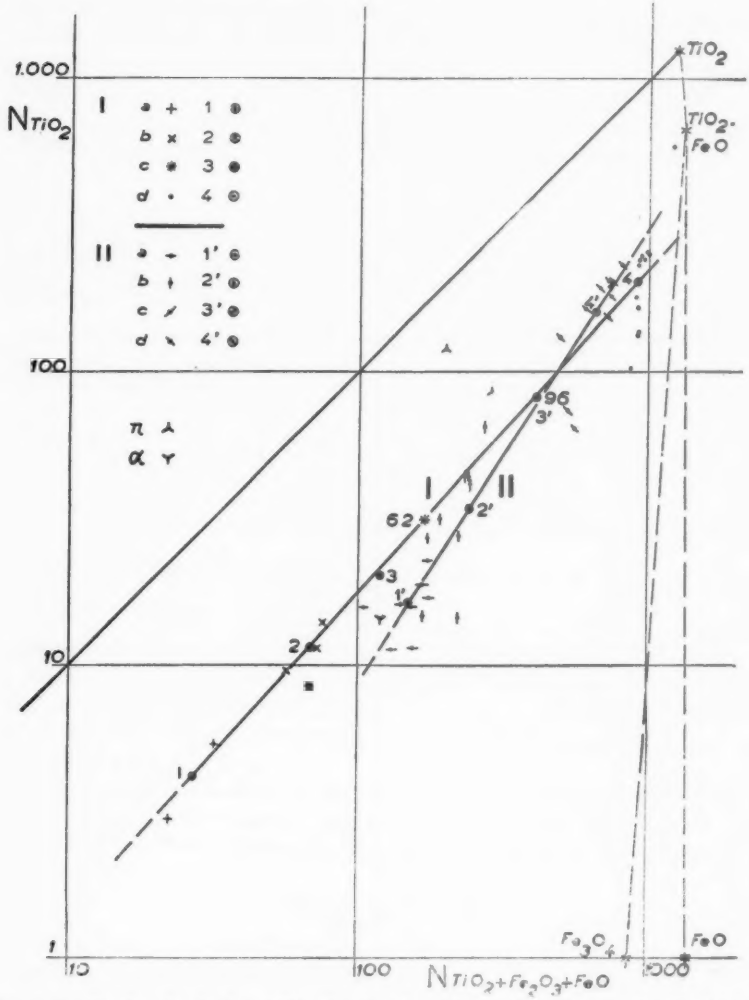

FIGURE 2.—*Number of molecules of TiO_2 plotted on logarithmic scale against number of molecules of $TiO_2 + Fe_2O_3$ for rock types (based on average of a number of analyses) of the "saturated" anorthositic series and "undersaturated" gabbroic series of the Adirondacks*

The location of the individual analyses averaged are also shown.

This method yielded better-characterized conclusions (Fig. 2).[5]

The first group (I. saturated rocks) includes: (a) analyses 57 and 58 (B-16 and B-17). Both are of rocks from the *central anorthositic mass*. The first one (57) is the

[5] To consult tables of analyses and lists of references, *see* the end of this chapter.

average analysis of 60 samples selected in the mass, powdered, and analyzed together; the second one (58) was made on the powder of 40 specimens gathered in different places in the same massive.

(b) the analyses of the *anorthositic border facies*. I proceeded in the same way: I took the average values of the analyses nos. 59, 60, and 61 (B-18, -19, -20). Each analysis was already the result of mixing, after powdering, of 10, 75 and 55 samples, respectively, selected in the border zone;

(c) the late differentiation facies with gabbroic features. They were represented in my documentation by the analyses nos. 62, 63 (B-24, -25); no. 62 is a norite in layers, cutting the anorthosite border facies; no. 63 is an anorthositic gabbro cutting the central facies.[6]

(d) the results of 14 analyses published in Kemp's work (1899) on the titaniferous ores of the Adirondacks. These ores come from the region of Sanford Lake, from Millpond Pit (66-K and 112-K to 115-K), and from Cheney Pit (118-K to 124-K); they are genetically related to the first differentiated series. Unluckily, these analyses only give TiO_2 and total Fe percentages. Consequently I calculated the number of FeO mols necessary to saturate the number of TiO_2 mols and then turned the remaining Fe into $FeO \cdot Fe_2O_3$.

The four average points 1, 2, 3, 4 (arithmetic average) (Fig. 2) are practically on a straight line.[7] A similar result is obtained with the second group formed by the undersaturated rocks called by Buddington basic metamorphic gabbros or metagabbros.

This differentiated series includes:

(a) metagabbros in the Northwestern Adirondacks, (1) in the zone of the Grenville rocks (79–81; B-50–52)

(2) in the granite zone; here occur amphibolites, metagabbros, and diabases (82–86; B-55–59). The average of all these analyses is fixed on the diagram by the point 1′ (Fig. 2).

(b) metagabbros in the Eastern Adirondacks. They are related to the ores of the Split Rock Mine type. There are nine analyses of gabbro masses or gneisses, metagabbros, granulites (with pyroxene, garnets, and andesine), and wall rocks of the ores (87–95:B-60–68).

The average of these is the point 2′ (Fig. 2).

(c) a mafic metagabbro with 30 per cent opaque elements.

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[6] It is at present impossible to take into the average analyses 63 and 64, of pegmatitic facies which are not common and in which the TiO_2 content is abnormal (Osborne, 1928). Moreover, their importance in volume is slight, and TiO_2 combines with calcium and silica to produce sphene.

Consequently their locations deviate a good deal from the normal averages (Fig. 2, point A).

A similar case is met with in analysis 67 (Fig. 2, point γ) of a gabbro, the mafic character of which is due to assimilation phenomena.

However, I thought it useful to plot the values of these analyses, though they are not taken into account in the average. These particular cases will be looked at later, when the problem limited to its magmatic phenomena will be cleared up a little more. It is to be noted that the pegmatitic facies have values higher than the average, while the assimilation facies has, on the contrary, lower values.

[7] The norite (62) is a rock of frequent occurrence and characteristic of differentiations with which titaniferous deposits are related (for instance Norway, Bushveld, Ural). Its point is exactly on the line joining the central and border anorthosites to the average of the ores (Fig. 2).

TABLE 2.—*List of analyses*

No.	Reference	Percentages			Molecular Numbers (×1000)			
		TiO_2	Fe_2O_3	FeO	TiO_2	Fe_2O_3	FeO	Total
57	B.-16	0.43	0.75	1.59	5.38	4.69	22.10	32.17
58	B.-17	0.24	0.35	1.24	3.00	2.19	17.25	22.44
1 = I.a.: Average					4.19			27.30
59	B.-18	1.12	1.31	3.89	14.–	8.20	54.–	76.20
60	B.-19	0.77	0.91	3.02	9.65	5.69	41.9	57.24
61	B.-20	0.92	0.66	4.17	11.50	4.13	57.9	73.53
2 = I.b.: Average					11.71			69.01
62	B.-24	2.54	1.69	9.27	31.8	10.60	129.–	171.4
63	B.-25	0.69	0.70	3.98	8.6	4.38	55.3	68.28
64	B.-26	9.65	1.40	5.32				
65	B.-27	6.88	1.59	14.12				
67	B.-30	1.15	1.35	7.00				
3 = I.c.: Average					20.2			119.85
		TiO_2	Fe total					
66	B.-28-L	13.38	59.56		167.–	300.–	467.–	934.–
112		10.73	63.45		134.–	333.–	467.–	934.–
113		19.74	53.62		246.5	237.–	484.–	968.–
114		20.24	55.62		252.5	247.5	500.–	1000.–
115		20.49	54.80		256.–	242.–	498.–	996.–
116		8.25	62.15		103.–	336.–	439.–	878.–
117		15.77	40.33		197.–	175.–	372.–	744.–
118	Kemp (1899)	10.91	62.65		136.–	328.–	464.–	928.–
119		20.03	51.22		250.–	222.–	472.–	944.–
120		19.52	51.30		244.–	225.–	469.–	938.–
121		18.70	51.44		234.–	229.–	463.–	926.–
122		14.52	56.60		181.5	277.–	458.5	917.–
123		4.–	62.66		50.–	357.–	407.–	814.–
124		47.50	36.86		593.–	22.–	615.–	1230.–
4 = I.d.: Average					203.–			910
		TiO_2	Fe_2O_3	FeO				
79	B.-50	1.31	3.44	7.35	16.4	21.5	102.1	140.–
80	B.-51	1.28	2.25	5.39	16.–	14.1	74.85	104.9
81	B.-52	1.53	6.14	8.01	19.2	38.4	111.2	168.8
82	B.-55	1.83	1.81	10.20	22.9	11.3	141.7	175.9
83	B.-56	1.28	1.08	9.40	16.–	6.75	130.5	153.25
84	B.-57	0.91	1.73	7.82	11.4	10.8	108.5	130.70
85	B.-58	1.37	1.93	10.69	17.1	12.1	148.5	177.7
86	B.-59	0.93	1.49	9.69	11.6	9.3	134.5	155.4
1′ = II.a: Average					16.3			151.1

TABLE 2—*Continued*

No.	Reference	Percentages			Molecular Numbers (×1000)			
		TiO_2	Fe_2O_3	FeO	TiO_2	Fe_2O_3	FeO	Total
87	B.-60-L	1.18	2.29	12.39	14.75	14.30	193.–	222.05
88	B.-61-L	2.54	2.17	10.60	31.80	13.60	147.3	192.7
89	B.-62	3.55	1.86	12.80	44.30	11.60	178.–	233.9
90	B.-63-L	1.20	1.39	10.45	15.–	8.70	145.–	168.7–
91	B.-64-L	3.37	1.61	13.81	42.1	10.07	192.–	244.17
92	B.-65-L	3.03	2.03	13.12	27.9	12.7	182.2	222.8
93	B.-66	2.22	1.73	9.79	27.8	10.8	136.–	174.6
94	B.-67	3.55	3.24	12.76	44.3	20.6	177.–	241.9
95	B.-68-L	5.26	4.63	12.99	65.7	29.–	180.5	275.2
2′ = II.b: Average					34.85			241.85
96	B.-69	7.43	6.60	19.80	93.–	41.2	275	409.2
3′ = II.c: Average					93.–			409.2
97	B.-70-L	5.21	30.34	22.81	65.–	190.–	303.–	558.–
98	B.-71-L	15.66	15.85	27.94	195.8	99.–	388.–	682.8
99	B.-72-L	16.45	20.35	28.82	206.–	127.–	400.–	733.–
100	B.-73-L	12.31	30.68	27.92	154.–	192.–	388.–	734.–
	Kemp (1910)							
105		14.70	38.43	23.40	183.7	242.–	325.–	750.7
106		10.55	11.52	21.34	131.9	72.9	296.–	500.–
107		13.07	11.16	28.35	163.3	69.7	394.–	627.–
108	Kemp (1899)	13.15	23.77	21.24	164.4	148.5	295.–	607.9
109		6.01	34.13	17.33	75.2	213.5	240.7	529.4
110		16.37	30.36	25.46	204.5	189.7	354.–	748.2
111		18.82	26.30	29.78	235.2	164.4	413.5	813.1
4′ = II.d.: Average					161.6			662.1

57. (B.-16).—Analysis of composite grab sample of 60 fragments of Marcy anorthosite from 10 localities in core of St. Regis-Marcy unit along road from Algonquin (Saranac quadrangle) to half a mile NW. of Rustic Lodge (Long Lake quadrangle). Analyst, R. B. Ellestad.

58. (B.-17).—Analysis of composite grab sample of about 40 samples of Marcy anorthosite across 2-mile section of Jay sheet, from 1 mile NE. of Jay to 0.7 mile west of North Jay (Ausable quadrangle). A quite uniform coarse-grained rock with a narrow range of variation in composition. Analyst, R. W. Perlich.

59. (B.-18).—Composite grab sample of 10 specimens of Whiteface gabbroic anorthosite facies from 5 miles along the strike of northeast border of anorthosite between Lake Flower and North of McCauley Pond (Saranac quadrangle). None of the more mafic facies commonly present in the border facies happened to occur along the belt sampled. Analyst, R. B. Ellestad.

60. (B.-19).—Composite grab sample of fragments of Whiteface facies of gabbroic anorthosite from 75 localities in area NE. of Reber, between it and the belt of Grenville passing through Sugarloaf Mountain, Willsboro quadrangle. Represents about 2 miles across the foliation along two traverses, 1½ miles apart. The percentage of mafic minerals was variable. No relics of Grenville or evidences of assimilation were observed. Analyst, R. B. Ellestad.

61. (B-20).—Analysis of composite grab sample of about 55 fragments of Whiteface facies from section 2½ miles across strike SE. from Long Pond outlet to 1½ miles NW. of Willsboro (Willsboro quadrangle), and N. of the highway. Analyst, R. B. Ellestad.

62. (B.-24).—Norite, sharply defined band in anorthosite of border facies, 1 7/8 miles W. of Gabriels (Saranac quadrangle). Analyst, R. W. Perlich.

TABLE 2—*Continued*

63. (B.-25).—Anorthositic gabbro sharply defined 15-foot sheet in Marcy facies on Keene Valley Road, 1 mile WNW. of intersection with main north-south highway. Elizabethtown quadrangle. Analyst, R. W. Perlich.

64. (B.-26).—Sphene gabbro pegmatite, quarry 3 miles E. of Wilmington, on south shoulder of Hamlin Mountain, Lake Placid quadrangle. Specimen is part of an 8-inch dike in Marcy anorthosite. Analyst, R. W. Perlich.

65. (B.-27).—Pyroxene gabbro facies of coarse gabbroic anorthosite; road cut 1 mile SSW. of Brown Pt. (Willsboro quadrangle). Analyst, R. B. Ellestad.

66. (B.-28-L).—Ilmenite-magnetite ore, Millpond ore body, near Lake Sanford (Santanoni quadrangle). Analyst, J. Rossi. Quoted by Kemp (1898, p. 388). Osborne (1928, p. 740) classifies this as a discordant ore body in anorthosite.

67. (B.-30).—Gabbro, quarry 2½ miles SSW. of Upper Jay (Lake Placid quadrangle). Analyst, R. Folinsbee.

79. (B.-50).—Metagabbro ¾ mile SE. of Geers Corners and about 750 feet south of B-51, Lake Bonaparte quadrangle, Analyst, R. B. Ellestad.

80. (B.-51).—Metagabbro, ½ mile E. of Geers Corners, about 100 feet south of the contact with limestone. A mottled black and white medium-grained rock with a moderate foliation. Analyst, R. B. Ellestad.

81. (B.-52).—Metagabbro, 1½ miles NNW. of Laidlaw School, Hammond quadrangle, upper part of Pleasant Lake sheet. Analyst, R. B. Ellestad.

82. (B.-55).—Garnet-hornblende amphibolite, 2½ miles ESE. of St. Regis Falls, Nicholville quadrangle. Gneissic, completely recrystallized rock. Analyst, A. Willman.

83. (B.-56).—Metagabbro $\frac{7}{8}$ mile NNW. of school No. 7, Santa Clara quadrangle. Analyst, A. Willman.

84. (B.-57).—Metagabbro (amphibolite); 1½ miles S. of Brandon (Malone quadrangle). Analyst, A. Willman.

85. (B.-58).—Metagabbro ½ mile south of Henry School, 1½ miles NE. of Croghan (Lowville quadrangle). Analyst, R. B. Ellestad.

86. (B.-59).—1$\frac{7}{8}$ miles WSW. of Jerden Falls and 3 miles S. of Caroll School, Lake Bonaparte quadrangle. Analyst, A. H. Phillips.

87. (B.-60-L).—Massive gabbro 2 miles S. of Elizabethtown (Kemp and Ruedemann, 1910, p. 55). Analyst, W. F. Hillebrand.

88. (B.-61-L).—Gneissoid gabbro, same locality as 87 (Kemp and Ruedemann, 1910, p. 55). Analyst, W. F. Hillebrand.

89. (B.-62).—Metagabbro, fine-grained granoblastic aggregate at contact of metagabbro with anorthosite. North border of Port Henry quadrangle on road along west side of Split Rock Mountain. Analyst, R. B. Ellestad.

90. (B.-63-L).—Metagabbro, wall rock of titaniferous magnetite, Split Rock Mine, Westport, Port Henry quadrangle (Kemp, 1899, p. 399-400). Analyst, W. F. Hillebrand.

91. (B.-64-L).—Woolen Mill gabbro, 1 mile W. of Elizabethtown (Kemp and Ruedemann, 1910, p. 55). Analyst, W. F. Hillebrand.

92. (B.-65-L).—Metagabbro, 1½ miles south of "The Glen", North Creek quadrangle (Miller, 1914, p. 32). Analyst, E. W. Morley.

93. (B.-66).—Pyroxene-garnet-olivine-andesine metagabbro. Core of dike extreme NE. end of Trembleau Mountain; ¾ mile W. of Trembleau Point, Plattsburg quadrangle. This specimen is typical of much of the metagabbro within the anorthosite. Analyst, R. B. Ellestad.

94. (B.-67).—Pyroxene-garnet-andesine granulite; border facies of same metagabbro dike as 93. This is a fine-grained average diameter 0.2 mm) wholly granoblastic polygonal equigranular rock, somewhat richer in normative ilmenite magnetite, and diopside, and with less plagioclase than the rock of the core but otherwise similar chemically. Analyst, R. B. Ellestad.

95. (B.-68-L).—Wall rock of titaniferous magnetite. Lincoln Pond, Elizabethtown quadrangle (Kemp, 1899, p. 406-407). Analyst, George Steiger.

96. (B.-69).—Mafic metagabbro band in gabbro, ¾ mile E. of McCauley pond (Saranac quadrangle) and ½ mile N. of railroad. The specimen is a dark equigranular gneissic rock. Analyst, A. Willman.

97. (B.-70-L).—Ross ore bed, Oak Hill about 1 mile N. of New Russia (Kemp and Ruedemann, 1910, p. 136). Analyst, W. F. Hillebrand.

98. (B.-71-L).—Ore, Split Rock Mine (Port Henry quadrangle). (Kemp and Ruedemann, 1910, p. 136).

99. (B.-72-L).—Ore, Tunnel Mountain mine, 3¼ miles SE. of Elizabethtown (Kemp and Ruedemann, 1910, p. 141-142). Ore consists of magnetite, ilmenite, brown hornblende, olivine, garnet, and plagioclase.

100. (B.-73-L).—Ore, Lincoln Pond (Kemp and Ruedemann, 1910, p. 145). Analyst, W. F. Hillebrand.

105.—Titaniferous ore of the Adirondacks (Split Rock—Westport). (Kemp, 1898, analysis no. 11). The wall rock of this ore is analyzed under no. 90. Analyst, Maynard.

106.—Titaniferous ore of the Adirondacks (Tunnel Mountain, Elizabethtown) (Kemp, 1898, analysis no. 1). Analyst, W. F. Hillebrand.

107.—Titaniferous ore of the Adirondacks (Little Pond, Elizabethtown-South Pit) (Kemp, 1898, analysis no. 2). Analyst, W. F. Hillebrand.

108.—Titaniferous ore of the Adirondacks (Kingdom mines, Elizabethtown) (Kemp, 1898, analysis no. 4). Analyst, Maynard.

109.—Titaniferous ore of the Adirondacks (Norway mine, Westport) (Kemp, 1898, analysis no. 6). Analyst, Maynard.

110.—Titaniferous ore of the Adirondacks (Iron Mountain, Elizabethtown) (Kemp, 1898, no. 8). Analyst, Maynard.

111.—Titaniferous ore of the Adirondacks (Little Pond, Elizabethtown, North Pit) (Kemp, 1898, no. 9). Analyst, W. F. Hillebrand.

112 to 124.—Analyses of ores near Sanford Lake (Newcomb Township, Adirondacks) (Kemp, 1898). The analyses no. 66 and no. 112, 113, 114, 115 are of ores from Millpond Pit; nos. 116 and 117 are from Cheney Pit, and nos. 118 to 124 from Sanford.

Analysis No. 96 (B-69) enabled me to fix the point 3′ fairly well in the line of the others.

This rock is intermediate between a true rock and an ore because of its high content in opaque elements (30 per cent). Therefore it is important to point out that it follows the general tendency of the established statistical relation.

(d) ilmenite-magnetite deposits in association with the metagabbros of the east. They are well known and were described by Kemp (1897; 1910) and by Osborne (1928). The point 4′ results from the average of 11 analyses (97–100; 105–111) published in Kemp's works, and some of which were cited by Professor Buddington.

DISCUSSION OF THE RESULTS

It must be pointed out that both series of computed points—1, 2, 3, 4 and 1′, 2′, 3′, 4′—, each of which belongs to a definite petrologically characterized magmatic entity, fall on two straight lines.

Thus, in a differentiated series, the number of TiO_2 mols., by weight unit of rock or ore, is a linear function, in a logarithmic representation, of the total number of $TiO_2+Fe_2O_3+FeO$ mols.

The relation can then be written:

$$\log N_{TiO_2} = k \log N_{TiO_2+Fe_2O_3+FeO} + \log a;$$

or

$$N_{TiO_2} = a.N^k_{TiO_2+Fe_2O_3+FeO} \qquad (1)$$

where N = mol number by weight unit; and
a and k = two parameters, different for each magmatic entity but constant in all the differentiated stages of a same magma. The formula expresses in another way that the molecular quantities of TiO_2 and $TiO_2+FeO+Fe_2O_3$ vary in a parallel direction following two geometrical progressions. The relative volumes of the various stages have not directly come into account. This can be justified by the fact that, for each stage in the process of the magmatic evolution, the equilibrium was supposed to be reached.

It is to be noted that I have drawn a straight line as the most simple and probable representation. I excluded the phenomena which may have occurred in an open system—that is, with addition or subtraction of materials. Where these intervene to an important extent, the virtual original composition is changed, and the phenomena must then be represented by a series of straight-line segments the whole of which could be represented by a curve.

The relation that binds TiO_2 to Fe_2O_3 and FeO seems, in the diagram, to be independent of the ratio $FeO:Fe_2O_3$. As the question is then to represent variations of relative quantities, I shall use ternary diagrams for the interpretation, in a future study.

It is pertinent to show what can be the meaning of the physico-chemical parameters a and k. Each of the lines I have drawn is applicable to a practical case. It is, of course, limited by the representative points of the weaker and of the higher average value of TiO_2.

For any line, the numerical values of the parameters a and k are easily computed:

a is obtained by lengthening the line representing one studied case until its intersection with the vertical line, the abscissa of which is

$$N_{TiO_2+Fe_2O_3+FeO} = 1 \tag{2}$$

If this condition is introduced in the preceding formula (1),

$$N_{TiO_2} = a \tag{3}$$

It follows that the value of a is the ordinate which corresponds with the abscissa point, equal to the unit.

Of course it is a computation artifice as the intersection point is only virtual. There is not necessarily a representative point of an analysis that corresponds to it.

k equals the angular coefficient of the line; it is greater than one when the concentration in TiO_2 increases more quickly than that of the total $TiO_2+Fe_2O_3+FeO$. In this case, the line forms with the horizontal an angle greater than 45°. It is a necessary condition for the formation of ilmenite deposits by differentiation.

For a given concentration ratio, characterized by a point in the diagram, the transformation of the magma can follow various processes determined by the various values of k. Consequently, the parameter k is a function of the usual thermodynamical agents which rule the differentiation—*i.e.*, the concentrations, temperature, and pressure. The last two agents are themselves dependent on the earth-crust level at which the deposit was formed.

Since one supposes that the magma evolution happens in equilibrium conditions, the masses of the magma must not be taken into account.

The parameter a is related not only to k but also to the "initial" concentrations. By the term "initial" concentrations, I mean the concentration conditions existing in a magma or in any residual fluid in process of differentiation. In fact, if by a point of the diagram, defined by a concentration ratio, $N_{TiO_2+Fe_2O_3+FeO}$, and characteristic for a given stage, a line can be drawn with an inclination equal to a certain value of k, then in this way, one finds the value of a on the ordinate, the abscissa of which is equal to the unit, as it was here defined by extrapolation.

As a conclusion, k defines the evolution processes of the magma, while a is more directly related to the concentration conditions.

REMARKS

Other agents may intervene, but it is too early to take them into account. The relation here proposed has no pretension to be either absolute or definitive. It is an average law for a great number. It must be considered as it is offered—as a first approximation. It neglects or tends to suppress less general phenomena. Corrective terms will be introduced later for particular cases, and these terms will take care of the minor variations.

However, some remarks force themselves to the mind. For the undersaturated, more basic series, a is smaller, and k bigger than in the case of the saturated group. Then the original magma is relatively poorer in TiO_2 and richer in FeO and Fe_2O_3. Perhaps it can also be supposed that the solidification and differentiation are quicker.

It is interesting to note that, when lengthened, the lines pass under the limit point 100 per cent $FeO \cdot TiO_2$; it means that under normal conditions, that is when no secondary phenomena occur, such as autometamorphism or pneumatolytic metamorphism, there is no free TiO_2 (rutile) associated with the ores.

The deductions and hypotheses one could draw from the diagram are numerous. But all of them would have the great imperfection of being based only on two related series of rocks of one determined region. The real importance of these first results will appear when one has available the same petrological, chemical, and metallogentical data for a whole series of regions.

CONCLUSIONS

I think I may draw the following conclusions:

In the course of the differentiation, the total number of TiO_2, FeO, and Fe_2O_3 mols as well as the number of TiO_2 mols increases continually.

When one considers the average values for the typical differentiated stages, this rule can be represented by a simple mathematical expression:

$$N_{TiO_2} = a.N^k{}_{TiO_2+Fe_2O_3+FeO}$$

The parameters, a and k, remain constant for each magmatic entity. The value of a is bound to the concentrations; k defines the differentiation process itself and is a function of the physico-chemical characters: pressure, temperature, concentrations.

The method of investigation here used could be applied to the study of many orthomagmatic deposits in which there is a connection between eruptive rocks and ores.

It could be applied to the chromite deposits (Wagner, 1928) by using for instance the relations of Cr_2O_3 with MgO, FeO, Fe_2O_3, Al_2O_3, etc.

The associations of Ti with Va, Ta, etc., also offer a vast field of investigation (Dunn and Key, 1937; Rankama, 1944).

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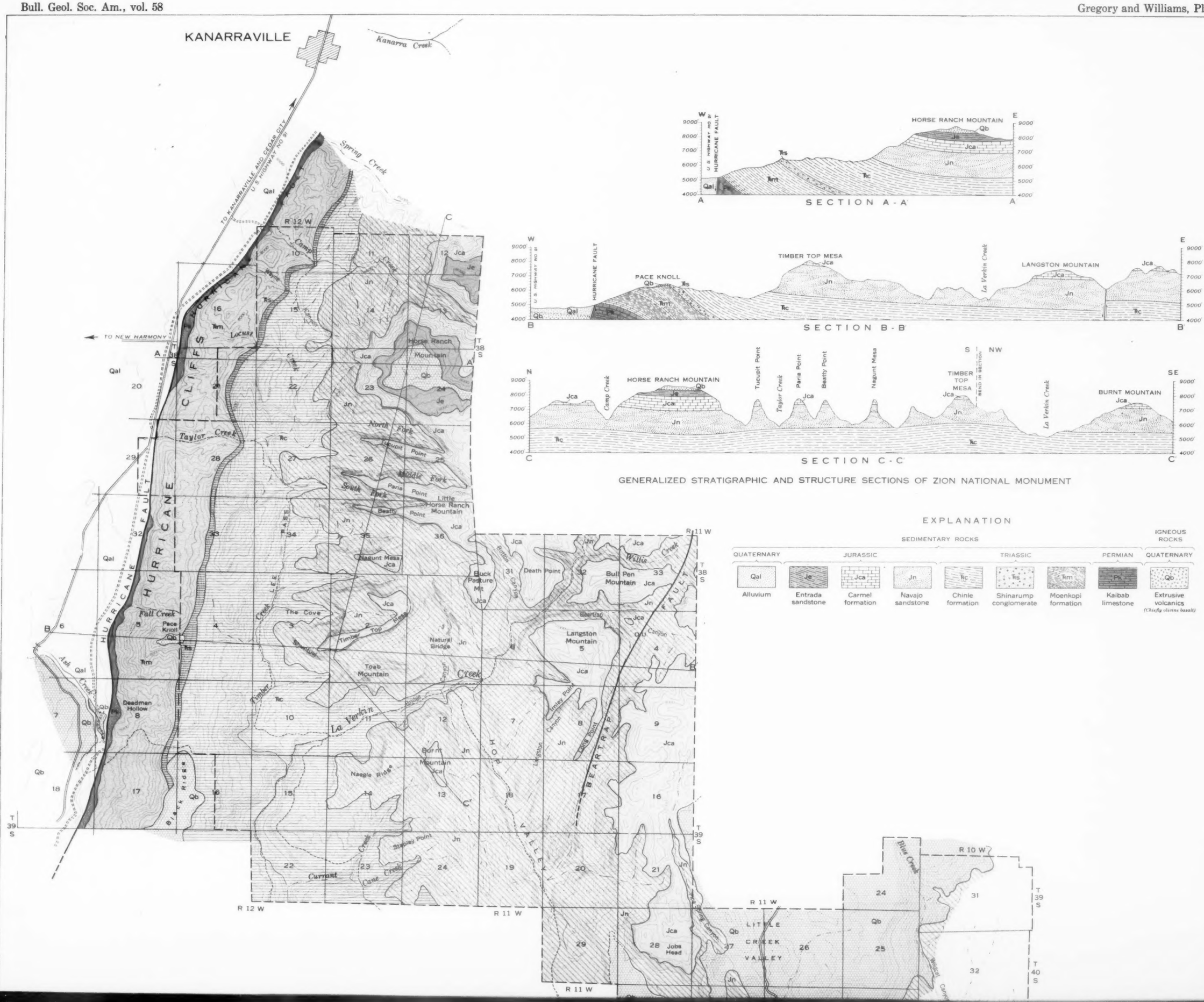


SECTION A-A'

SECTION B-B'

SECTION C-C'

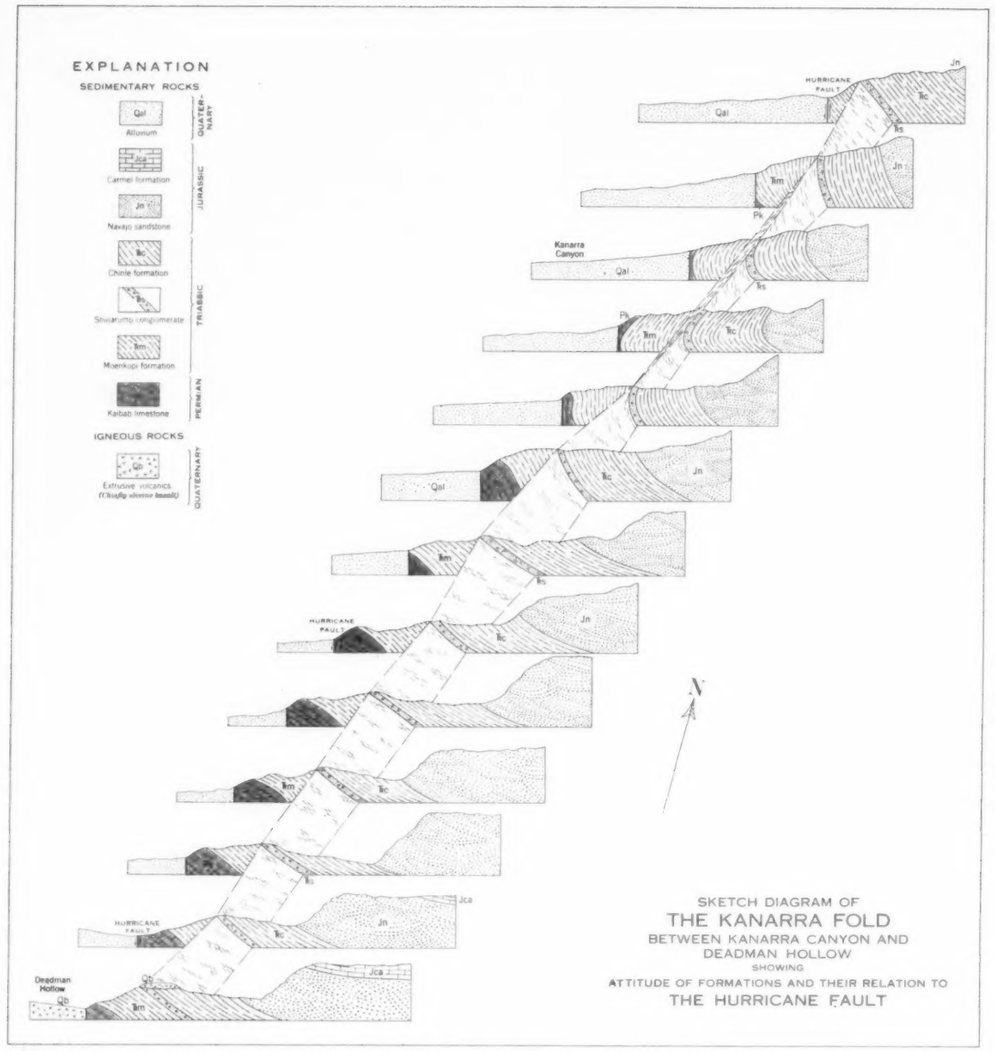
GENERALIZED STRATIGRAPHIC AND STRUCTURE SECTIONS OF ZION NATIONAL MONUMENT

EXPLANATION

SEDIMENTARY ROCKS								IGNEOUS ROCKS
QUATERNARY	JURASSIC		TRIASSIC				PERMIAN	QUATERNARY
Qal	Je	Jca	Jn	Rc	Rs	Rm	Pk	Qb
Alluvium	Entrada sandstone	Carmel formation	Navajo sandstone	Chinle formation	Shinarump conglomerate	Moenkopi formation	Kaibab limestone	Extrusive volcanics (Chiefly olivine basalt)

GEOLOGIC MAP
OF THE
ZION NATIONAL MONUMENT, UTAH

SKETCH DIAGRAM OF
THE KANARRA FOLD
BETWEEN KANARRA CANYON AND
DEADMAN HOLLOW
SHOWING
ATTITUDE OF FORMATIONS AND THEIR RELATION TO
THE HURRICANE FAULT



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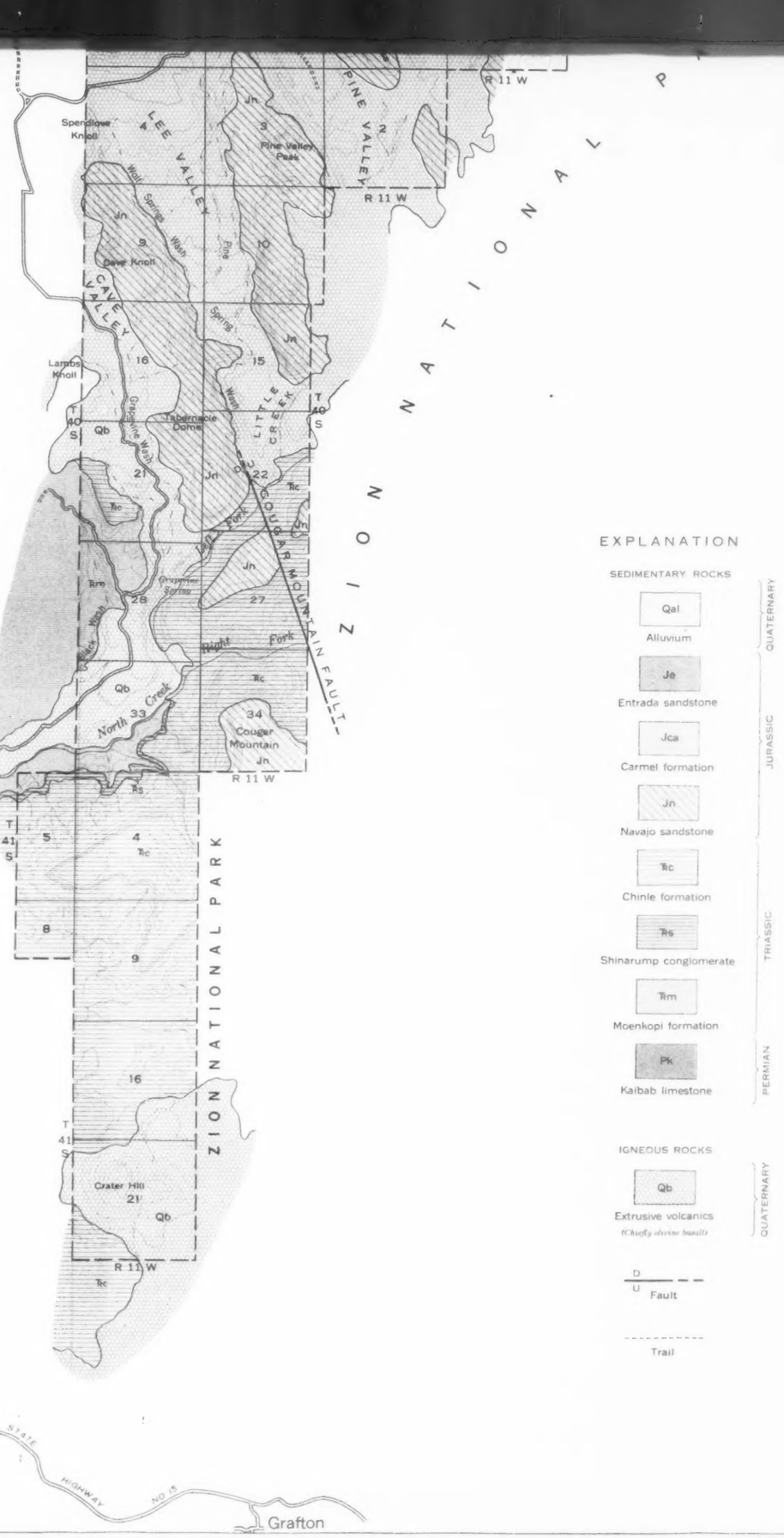
GEOLOGIC MAP
OF THE
ZION NATIONAL MONUMENT, UTAH

BY
HERBERT E. GREGORY AND NORMAN C. WILLIAMS

TOPOGRAPHIC BASE MODIFIED FROM MAP BY R. T. EVANS

SCALE 1:63,360
(Contour interval 100 feet)

2 1 ½ 0 1 2 MILES
10000 5000 0 5000 10000 FEET



TOPOGRAPHY AND GEOLOGY OF ZION NATIONAL MONUMENT, UTAH

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ZION NATIONAL MONUMENT, UTAH

BY HERBERT E. GREGORY AND NORMAN C. WILLIAMS

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ABSTRACT

The Zion National Monument in Washington and Iron counties, southwestern Utah, includes approximately 5000 feet of sedimentary rocks, profoundly and intricately eroded; extrusive volcanics of two ages; and faults and folds of large displacement. The oldest sedimentary formation exposed is the Kaibab (Permian). Above it lie the Moenkopi, the Shinarump, and the Chinle formations of Triassic age; the Navajo sandstone, assigned to the Jurassic; and the Carmel formation and Entrada sandstone of known Jurassic age. The igneous rocks are basaltic cones and lavas. In the western part of the Monument the pre-Tertiary Kanarra fold has affected all the sedimentary rocks exposed. The fold was broken essentially parallel to its axis by the Hurricane fault, which in late Tertiary and Quaternary times disturbed the sedimentary rocks and most of the lava flows. Generally east of the area traversed by the Kanarra fold and the Hurricane fault the rocks are nearly horizontal; the displacement produced by faults is relatively slight. The physiographic history of the region is substantially that of the Colorado Plateau, of which the Monument is a part. Two major cycles of erosion are outlined, each initiated by faulting accompanied by regional uplifts. Conspicuous erosion features are deep, vertically walled canyons, remnant flat lands, surfaces cut across tilted rocks, hogbacks, and thick accumulations of gravel on canyon floors, now in process of vigorous removal. The region has no permanent inhabitants; it is a reserved scenic area in the midst of summer grazing lands.

INTRODUCTION

The Zion National Monument, created by Presidential Proclamation January 22, 1937, comprises about 76 square miles in Washington and Iron counties, Utah (Fig. 1). Essentially it is a westward extension of Zion National Park and thus an enlargement of the area in southern Utah set aside "for the enjoyment of natural scenery and the protection of nature and wild life."

Though it is a region of much scenic interest and lies near centers of population, the Monument is little known; it is inaccessible to casual travelers. The adventurous few who traverse the steep, winding, poorly developed road from Virgin City up Grapevine Wash, around Spendlove Knoll, across the Kolob Terrace, and down the precipitous Hurricane Cliffs to Kanarraville, or Cedar City, may enjoy near-by views of the volcanoes and lava flows and the characteristic vegetation and distant views of the red walls and towers along La Verkin Creek. But, for the tens of thousands who each year pass along Federal highway 91 (the Arrowhead trail) at the westward edge of the Monument, the view eastward is cut out by the sturdy Hurricane Cliffs. The Monument, however, is crossed by a well-marked trail (in early days occasionally used as a wagon road) that leads from Federal highway 91 up Taylor (Dry) Creek, across Lee Pass, down Timber Creek, and across La Verkin and Currant creeks to Smith Mesa. Trails through the crooked, narrow La Verkin

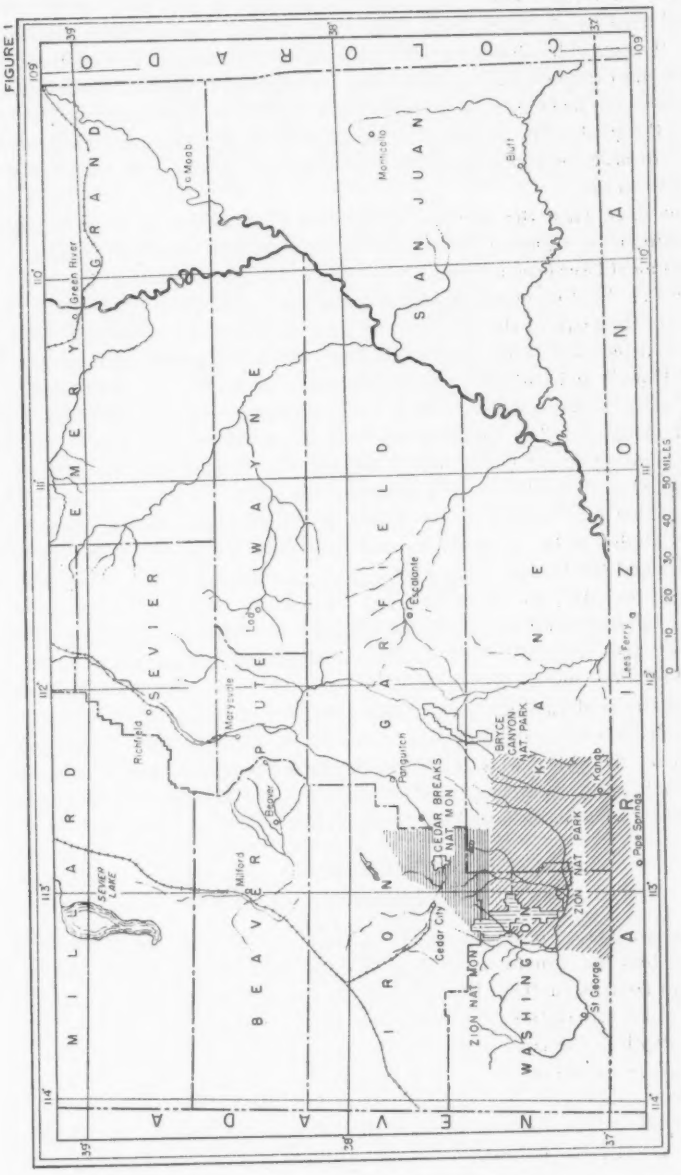

FIGURE 1.—*Outline map of southern Utah*

Showing position of Zion National Monument and its relation to adjacent areas covered by recent geologic surveys. Zion Monument represented by vertically ruled lines; Zion Park region represented by diagonally ruled lines; and Eastern Iron County represented by horizontally ruled lines.

Canyon and the broad-floored Hop Valley are established routes for cattle drives, and a trail used by stockmen leads down Camp Creek. By avoiding quicksands and dense thickets of brush other narrow valleys may be traversed on horseback, but most of the short canyons and the slopes that lead upward to the base of the gigantic rock buttresses can be followed only on foot, and only experienced mountain climbers can ascend the great cliffs. Timber Top, which from an airplane appears as a broad, flat surface densely covered with native vegetation, has proved to be inaccessible to livestock and to men.

Since the days when the Mormon settlements in southwestern Utah expanded into the surrounding regions (1860–1870), the highlands that include the Zion National Monument have been intimately known to the local stockmen and hunters, but the scientific study of its interesting flora, fauna and topographic features was long delayed. On the maps of the Wheeler and the Powell surveys, completed in 1872, the region is depicted in highly generalized form, and in the pioneer geologic reports of Gilbert, Howell, and Dutton incidental references are made to the volcanoes, lava flows, and canyons as representatives of features displayed in near-by areas, more convenient of access. The southwestern part of the Monument was briefly described by Huntington and Goldthwait (1904) and the southern part was mapped by Gregory (1938) in connection with a survey of the Zion Park region. Incident to the proposal that the "canyons of the Kolob" be set aside as a Federal reservation, preliminary studies of the entire Monument were made by officers of the National Park Service and the United States Geological Survey during 1930–1936. Since its establishment in 1937, the Zion National Monument has been topographically mapped by Evans, (1938) and its fauna and flora investigated by Marion (1937). The present report is based on miscellaneous observations and records made during the years 1930-1938 and on systematic mapping in 1940 and 1941. The field work has been greatly facilitated by the generous assistance of Walter Beatty, who since his boyhood has traversed the canyons and crossed the uplands of the Monument; of J. C. Anderson, naturalist, who took photographs at designated view points; and of Paul R. Franke, Superintendent, and Don Jolley, Chief Ranger, of Zion National Park, whose jurisdiction includes Zion National Monument.

GEOGRAPHY

CLIMATE

A few instrumental records, reports of stockmen, and observations of the present survey show that the climate of the Zion National Monument is similar to that of other plateau lands in southern Utah, where the controlling factors in precipitation and temperature are altitude, the prevailing southwesterly winds, and the distribution and depth of the large canyons. In the central part (altitude 7500 to 8500 feet) the average annual precipitation is estimated as 30 inches, compared to about 10 inches along its western edge (altitude 4500 to 5500 feet). This increase begins at Hurricane Cliffs where, because of an abrupt increase in altitude, the winds are drained of considerable moisture. On the highlands, rains are expected in late spring, summer, and early fall and often are heavy and frequent in July and August.

Most of the precipitation, however, is snow; in fact, snow fall is the climatic factor that most concerns the growth of vegetation, the behavior of streams, and consequently the utilization of the region by man.

No special study has been made of the snow fall in the Monument, but it is doubtless roughly comparable with that on near-by Webster Flat, where it measured a mean annual depth of 46.5 inches for 1927–1938—a minimum 22 inches (1934) and maximum 83 inches (1937). Stockmen report that snow may fall at any time between September and June, rarely even in July and August, and in most years it mantles the surface from November to April.

Though instrumental records are lacking, it seems obvious that the temperatures of the area are generally lower and subject to less extreme daily, monthly, and annual ranges than those at Cedar City (altitude 5805 feet), the nearest meteorological station, which records mean monthly temperatures of 41° to 63° for spring and fall, 68° to 72° for summer, and 30° to 35° for winter; daily ranges exceed 40°, and the annual range is 118°—99° and −19°. Except on the floors of the deeper canyons, temperatures probably never exceed 80°. From April to October the weather is delightful; from November to March temperatures fall below zero. In normal years the period without killing frosts is probably about 60 days.

Because of the inhospitable climate the Monument is insuitable for settlement. At the higher levels the growing season is too short for field crops and on the warmer canyon floors there is little arable land.

PLANTS AND ANIMALS

In Zion National Monument the large ranges in altitude, in type of exposure, soil, and amount of ground water permit the growth of many of the plants common to southern Utah. At altitudes below 7000 feet the dominant trees are piñon pine (*Pinus edulis*) and juniper (*Juniperus utahensis*), constituting the "pigmy forest" or the "woodland type" in the upper Sonoran zone (Pls. 5, 6, 8). Among the piñons and junipers, sage brush grows profusely, and, less abundantly, such shrubs as cliff rose, service berry, manzanita, mountain mahogany, and squaw bush. At altitudes between 7000 and 8500 feet the dominant tree is yellow pine (*Pinus ponderosa*), in many places accompanied by oak, buck brush (*Symphoricarpus*), service berry (*Amelanchier*), bitter brush (*Purchia*), and black or birch-leaf mahogany (*Cercocarpus montanus*). At the highest altitudes in the Monument and adjoining areas northward some spruces and firs rise from groves of aspen, but on most of the highest knolls the ground cover consists of grasses intermingled with ground juniper and other low shrubs (Pl. 3). Long stretches of canyon walls, cliffs, volcanic cones, and lava flows are wholly or partly devoid of vegetation. The botanical evidence shows clearly that the palatable plants in the original vegetation of Zion National Monument were sufficiently abundant to support large herds during the necessarily short grazing season and that, in place of the endemic vegetation, annual and biennial weeds now cover most of the stream flats, and sage brush occupies large parts of the interstream areas. In many places the earmarks of overgrazing are conspicuously present. The destruction of the protecting plant cover on steep slopes and canyon floors has

facilitated gullying and sheet-flood erosion, thus exposing considerable areas of bare rock and infertile sand and gravel.

The native animals in the Zion National Monument are those found elsewhere in southern Utah, where rough topography, a wide range in altitude, rainfall, and temperature, and the relative abundance and distribution of vegetation provide an exceptionally large variety of habitats for a relatively few species. As noted by Marion (1937), 13 species of mammals comprised 275 individuals, and 34 species of birds, 572 individuals. Of the larger mammals, deer are fairly numerous, but mountain sheep, bears, and beavers, which once formed part of the fauna, have disappeared. The predatory animals, though systematically trapped and hunted, are still in evidence. Reptiles are scarce on the highland areas but annoyingly numerous in the low-lying canyons.

TOPOGRAPHIC FEATURES

General expression.—Zion National Monument is part of the Kolob Terrace, one of the rock platforms that, beginning with the Uinkaret Plateau along the Colorado River, rise in steps thousands of square miles in areal extent and 1000 to 2000 feet high—steps that lead to Markagunt Plateau, 10,000 feet above sea level (Fig. 1; Pl. 9). In the Monument about half the surface lies above 7000 feet and about one-tenth below 5000 feet. The highest point is Horse Ranch Mountain (altitude 8742 feet), and the lowest the floor of North Creek at the mouth of Black Wash (altitude 4100 feet) (Pl. 1). In its general expression the topography of the Monument closely resembles that described for the adjoining Zion Park region (Gregory, 1938). Its outstanding features are high cliffs, buttresses, deep narrow canyons, sharply outlined hogbacks, and stretches of high-lying flat land (Pls. 2, 3, 6).

In the high eastern part of the Monument the general surface is formed of resistant limestone into which are incised numerous trenches, all much alike in longitudinal and transverse profiles and above which rise a few low, broad mounds. Detached parts of the upland are such huge mesas as Timber Top, Langston Mountain, and Bull Pen Mountain. This pattern is prevalent also in the southern part of the Monument, though here the surface beds are sandstones and lavas. In contrast with these generally flat surfaces and mesa tops, the western part of the Monument displays a series of roughly parallel ridges and intervening valleys.

These larger differences in general topography reflect control by composition, texture, and attitude of the rocks (Pl. 2). In fact, the sculpture of the Monument may be described, almost completely in terms of stratified rocks (hard and soft); except along Hurricane Cliffs features produced by faulting and folding are few and relatively inconspicuous. Resistant rocks hold up the broad benches and mesas and underlie extensive level surfaces; they also are responsible for the hogback ridges and resulting steep slopes. The cliffed borders of plateau remnants and of canyons and the benches on long slopes are likewise determined by hard rocks. The surface exposures of weak beds are in general characterized by slopes or by gently undulating topography and mark the position of innumerable streamways.

This topographyas developed by the erosion of sedimentary rocks has been considerably modified by the superposition of lavas and volcanic cones. Remnant lava

FIGURE 1. VIEW OF ZION NATIONAL MONUMENT

From point near old Fort Harmony, looking across Hurricane Cliffs (lowest escarpment) eastward 8 miles to Horse Ranch Mountain (upper left) and the broken rim of Kolob Terrace (center and right skyline). Highway 91 (Arrowhead Trail) runs north-south at the base of the cliffs. Altitude of foreground 5000 feet; of Horse Ranch Mountain 8700 feet.

FIGURE 2. VIEW OF CENTRAL PART OF ZION NATIONAL MONUMENT

Looking northwest. Eastward-tilted Moenkopi strata form exposed back slope of Hurricane Cliffs; Chinle strata the lowlands (lower left); and Navajo sandstone capped by Carmel limestone borders the Kolob Terrace (upper left center). Lava flows occupy Lee and Cave valleys. Length of view about 15 miles. Altitude of surfaces exposed 5000 to 8500 feet (U. S. Army Air Corps).

REGIONAL VIEWS OF ZION NATIONAL PARK

FIGURE 1. GENERAL VIEW

FIGURE 2. VIEW BACK OF CANYON HEADS AND CLIFF WALLS THAT MARK THE TERRACE EDGE

FIGURE 3. UNDRAINED BASIN

SURFACE OF KOLOB TERRACE

flows cap Horse Ranch Mountain, Black Ridge, and Pace Knoll, and in the area that includes Pine Valley, Lee Valley, Cave Valley, and North Creek, lavas are widespread. The volcanic cones, Firepit Knoll and Crater Hill, are prominent landmarks.

The grandeur of the cliffs, canyons, towers, and terraces is enhanced by coloring. The walls of the canyons through which flow the upper reaches of La Verkin, Hop, Taylor, and Camp Creek are bright red. Those farther downstream present bands of gray, white, yellow, lavender, and innumerable shades of red and brown. Along North Creek and its tributaries black lavas add an exotic tone to the brightly variegated rocks in the Belted Cliffs.

Streams.—The streams in the Monument are within the drainage basin of the Virgin River, which joins the Colorado River in the artificial Lake Mead. The western part is drained by Spring, Camp, Wayne, and Taylor creeks and a score of smaller streams that reach the Virgin through Ash Creek; the eastern and southeastern parts by Wildcat, Pine Springs, Little, Grapevine, and Black creeks, tributaries to the through-flowing North Creek; and the central part by La Verkin Creek, which on its way to the Virgin River is joined by Bear Trap, Willis, Button, Hop, Timber, and several smaller creeks. These streams make an integrated system by which the region is thoroughly drained. The only bodies of standing water are tiny ponds on landslides and in depressions on lava flows.

Bare rock is more widespread than soil, and most of the precipitation is represented in the runoff, which fluctuates widely and irregularly in response to the erratic distribution of rainfall. During the 4 or 5 months when large parts of the region are thickly mantled with snow the streams on the grass-covered flat highlands cease to flow, and those at lower altitude carry little water. During the spring scores of streams are through-flowing. During the summer and fall all the streams fluctuate in volume in accord with local showers. Camp Creek, Wayne, Taylor, and North creeks, also La Verkin Creek and its long tributaries, Timber and Hop creeks, are perennial. Many streams are perennial only at their sources; still others are intermittent or ephemeral. As observed in the summer season, the typical intermittent stream rises in a spring at the head of a box canyon and after flowing a short distance becomes lost in sand or boulders. Farther on it reappears, particularly in places where bare rocks form the valley floor. Its changing volume is shown by cut banks and by coarse detritus and driftwood perched on the valley sides. The ephemeral streams on unvegetated slopes are fed by rain that gathers into gullies and sweeps from the surface wind-blown sand, disintegrated rock, and stray bits of vegetation. Into the perennial and intermittent streams the ephemeral streams dump masses of debris, converting them into turbulent muddy floods. The varying continuity and volume of intermittent streams is largely a measure of the number and spacing of the tributary ephemeral streams.

The streams in the Monument are short, and their runways steeply inclined. The principal streams and their longest tributaries start on the surface of the Kolob Terraces at altitudes of 7500 to 8500 feet and, after flowing 3 to 10 miles, leave the Monument at points 4500 to 4800 feet above sea level. Pine Spring Creek, which runs for some distance on the south-sloping undissected highlands and then drops into North Fork Canyon, descends at an average rate of 300 feet a mile. Taylor

Creek and other tributaries flowing west to Ash Creek from the highlands about Horse Ranch Mountain have gradients exceeding 500 feet a mile. Fall Creek and similar short streams that have carved the face of the Hurricane Cliffs descend fully 1000 feet a mile. Over the faces of cliffs many ephemeral streams drop as waterfalls. Thus the streams in the Monument, unlike those in many other regions, present a succession of waterfalls, rapids, and stretches of relatively smooth water at irregular intervals. The steep gradients make the streams powerful agents of transportation. At low-water stages they are continuously moving sand and silt and in times of flood carry great quantities of fine and coarse rock waste across steep slopes and gentle slopes and push forward the boulders and angular blocks dropped from the adjoining cliffs.

Valleys.—Most valleys in the Zion National Monument are narrow, flat-bottomed, steep-sided, meandering gorges which ascend headwards up unevenly placed steps. Their alinement is controlled by relative rock hardness, by inclination of the strata, by zones of faulting, and, to a large extent, by joints. Valleys such as Timber Creek and the north-and south-flowing tributaries to Taylor, Locust, Wayne, and Camp creeks are fairly straight; they have been developed by subsequent streams that for considerable distances follow the trend of soft rocks. For parts of its course Pine Springs valley follows the fairly straight edge of a lava flow; tributaries to Hop, Beartrap, and Willis canyons depart little from the trend of the Beartrap fault; and the western tributaries to Timber Creek flow down the dip slope of a monoclinal fold. Especially effective in determining the direction and spacing of valleys are the innumerable vertical and oblique joints that pass entirely through the thick beds of sandstones, and in places continue into the adjacent limestones and shales, which also have their own fracture planes. The erosion that has left standing the giant buttresses at the head of Taylor Creek and along Timber Creek, and such lofty mesas as Burnt Mountain, Timber Top, Langston Mountain, and Buck Pasture, was guided by joints, along some of which slight faulting has occurred. Many short valleys are located along joints, and commonly the meanders in the canyons follow the larger cracks. A tributary to Hop Valley follows joints north, east, south, west, and north, thus completing a circuit of 360 degrees. Though many drainage channels are thus adjusted to structure, many disregard it in part, and others entirely. Thus the south-flowing tributaries to North Creek cross lava flows and ridges of sandstone, and North Creek itself crosses the Cougar Mountain fault with no change in general course. Particularly noticeable is the discordance of trend and structure in the valleys that carry water to Ash Creek. All of them cross steeply tilted strata in a direction opposite to the dip. Among the existing structural features the routes of these streams are evidently anomolous. Like most of the streams in the Monument their general course, their angular bends, and their meandering curves were doubtless established on the relatively flat lands of the original Kolob Terrace, which once extended westward beyond the Hurricane fault. While cutting their channels they retained substantially their original alinement.

In longitudinal profile the floors of valleys in the Monument are very uneven. In most canyons and in many more open valleys the floor is a series of steps, commonly bare ledges, between stretches of fairly level sand and coarse debris. In

FIGURE 1. OLD LANDSLIDE (MIDDLE DISTANCE) THAT BLOCKED STREAM CAUSING PONDING (FOREGROUND)

FIGURE 2. LOOKING UPSTREAM EAST FROM LANDSLIDE
Valley floor thickly covered with fine alluvium and lacustrine sediments including peat.

FIGURE 1. HANGING VALLEY, BRANCH OF TIMBER CREEK, CUT IN NAVAJO SANDSTONE

FIGURE 2. SPRINGDALE MEMBER OF CHINLE FORMATION
In lower wall of La Verkin Canyon at mouth of Current Creek.

FIGURE 3. LOWER RED SANDSTONES OF MOENKOPI FORMATION
Terminated by the Hurricane fault (left), north side of Taylor Creek.

general the steps, especially in valleys tributary to the larger streams, are wider and more numerous near the headwaters and near the mouths, thus making the generalized profile a curve steep at both ends. The larger valleys of the region—North Creek, La Verkin Creek, and Ash Creek—meet their master stream, the Virgin River, at grade, and a few other streams follow this pattern; but the junction of most valleys is marked by precipitous slopes or ledges over which tributaries descend in steep slots. Many tributaries of the second and third orders occupy hanging valleys, some of them so poorly defined that ephemeral sheet streams drop directly to the floors of canyons (Pl. 5, fig. 1). No valley observed in the Monument is graded throughout its course, and few of them are for more than a mile. Traverse of valleys involves frequent detours and scrambles over rock steps on the floor.

In cross section the valleys range from troughs with steeply sloping sides to deep, narrow, vertically walled trenches (Fig. 2; Pls. 1, 5, 7, 12). Shallow, broad valleys with flaring sides are restricted to the expanses of flat highlands between Jobs Head and Horse Ranch Mountain. Timber Creek and other valleys developed along the trend of the inclined strata in the Kanarra fold are generally bordered by walls on one side and by slopes on the other, and valleys that cross the tilted rocks present walls and flaring sides at intervals in accord with the relative hardness of the rocks encountered. Most of the valleys in the Monument are sunk into horizontal or slightly tilted, resistant beds of great thickness or into soft rocks protected from erosion by overlying hard rocks, and are consequently straight-walled, deep, and narrow. Thus upper La Verkin Canyon for a considerable distance is 2000 feet deep and less than 50 feet wide, and the three forks of Taylor Creek flow for about a mile between close-pressed, almost vertical walls more than 1000 feet high; their upper parts are mere slots, barely wide enough for passage by pack horses.

On the poorly marked drainage divides between tributaries to North Creek and those flowing eastward to Zion Canyon (beyond the limits of the map) some stream channels are being lengthened, and other shortened, by the slow shifting of divides. The steep headwater tributaries of the La Verkin and of the streams that flow westward to Ash Creek start abruptly in box-headed canyons where they are vigorously undercutting and thus capturing the stream channels that trend in an opposite direction. At Lee Pass former tributaries to Timber Creek have been captured by the more steeply inclined South Fork of Taylor Creek.

Minor features.—Because the rocks in Zion National Monument are both horizontal and tilted and range in composition and texture from soluble gypsum, shale, and weakly cemented sandstones and shales to resistant conglomerates, compact sandstones, limestone, and lava, the minor erosion features produced by weathering, ground-water seepage, and stream wear are of almost endless variety. They add charm to the landscape dominated by great cliffs and canyons and aid in the interpretation of recent geologic history. Of particular local interest are the landslides, the alluvial terraces, and the carvings in the massive sandstone.

In this region of steep slopes and vertical cliffs scoured by innumerable canyons, gulches, and sluiceways, disintegrated rock finds few resting places; extensive, thick accumulations of talus are rare. From the sheer cliffs blocks of rock quarried by frost fall onto steep slopes from which all but the larger fragments are rapidly stripped

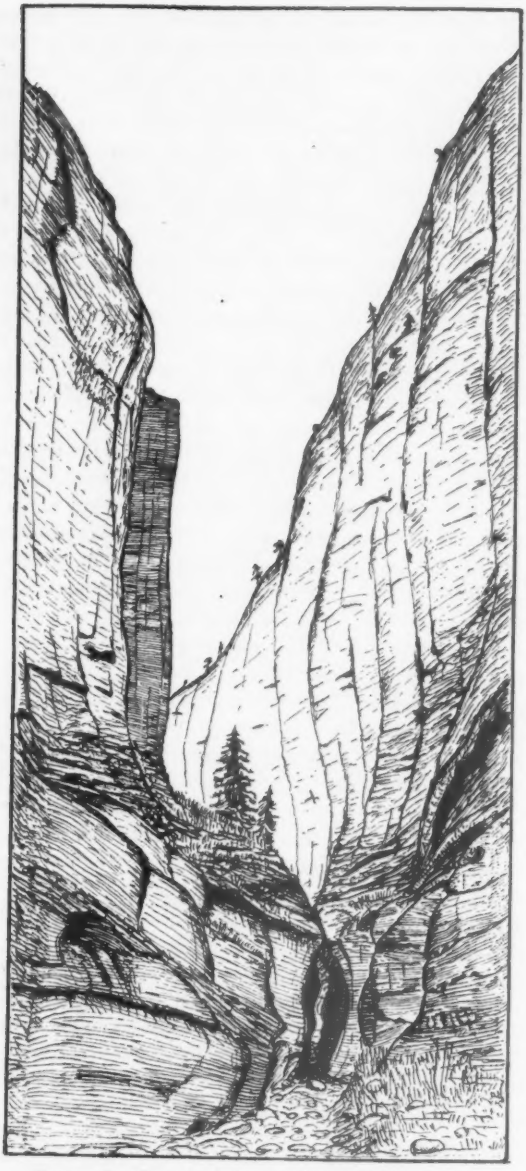

FIGURE 2.—*Canyon of the south fork of Taylor Creek*
Cut into Navajo sandstone. Depth 1500 feet; width at bottom 6 to 15 feet; width at top 110 to 160 feet.

by torrential showers, and from the high canyon walls they drop directly to the stream beds. Likewise from the steep-sided tributary valleys most of the superficial debris is carried promptly to the master channels. Therefore most of the material that under different conditions might form talus lies at the bottoms of valleys in fans, deltas, and bars made of gravel intermingled with angular boulders. Some of it remains as huge isolated blocks on the bordering slopes. In the general sparseness of talus in favorable position for mass movement and the absence of water-soaked strata in contact with impervious "sliding beds", most landslides in the Monument are caused by the detachment of slices of rock from high cliffs—masses of sandstone or lava that fall to the cliff base and spread over the valley floor. In Hop Valley a landslide of such origin—a pile of angular boulders imbedded in finer debris—completely blocked the stream, forming a long, rock-walled pond that discharged its water through the porous gravel (Pl. 4). On attaining suitable height the ponded water overran the slide and during the "big flood" of June 1908 developed the crooked runway through which Hop Creek descends to La Verkin Creek as a waterfall.

Many streams in the Monument are bordered by alluvial terraces that hem in the channel and extend outward to the base of the inclosing canyon walls. Some of them are continuous for miles, others are broken into flat-topped sand banks, widely or narrowly spaced. In some valleys two or more terraces of different breadth form steps. For considerable stretches along La Verkin Creek and the more swiftly flowing parts of other streams terraces are absent—the alluvium has been entirely swept away. On the other hand, along some tributary streams the entire original valley fill remains.

Most of the terraces seem to consist of evenly stratified white sand—the result of uninterrupted sedimentation that ceased only when the present trenching began. Closer examination, however, reveals differences in composition, unconformity in bedding, and manner of contacts with the adjoining rock walls, thus indicating irregular alternating periods of aggradation and degradation. Along Hop Creek the alluvial walls that rise vertically 10 to 40 feet above the stream bed are chiefly thinly bedded fine sand and clayey silt and include beds of peat, 3 inches to 4 feet thick. This fluviatile and lacustrine material indicates a former flood plain of very gentle slope which from time to time and in various places held ponds and swamps. Deposition was facilitated by a landslide which blocked the mouth of the valley with a huge mass of boulders and finer debris, through which even yet Hop Creek has not established unobstructed passage (Pl. 4). The existing terraces are youthful. Walter Beatty states that as late as 1900 Hop Valley was meadowland in which a shallow stream flowed through groves of boxelder and ash.

The sculpture that everywhere in southern Utah is characteristic of the thick beds of Triassic and Jurassic sandstone is well displayed in Zion National Monument. It is particularly prominent in the Navajo sandstone which walls in the deep canyons and forms the great cliffs at the edge of the Kolob Terrace. This mass of friable, cross-bedded, strongly jointed sandstone is marked by flat surfaces, alcoves, fluted columns, panels, towers, domes, and blind windows, some of which are elaborately decorated with picturesque small-scale carvings. In La Verkin Creek about a mile above the mouth of Hop Valley a cliff cave 300 feet wide and 200 feet high has been

worn about 100 feet back into the canyon wall, and in Bridge (Crystal) Canyon stands a beautiful natural arch.

SEDIMENTARY ROCKS

GENERAL RELATIONS

The sedimentary rocks in Zion National Monument are of Permian, Triassic, and Jurassic age; the unconsolidated deposits, of Quaternary age (Pleistocene ? and Recent epochs). They include marine, brackish-water, and fresh-water deposits. Sandstone predominates, in decreasing order of abundance are limestone, shale, conglomerate, and gypsum.

All the formations in the Monument are represented in adjacent regions, into which they are readily traced. Because the stratigraphy of the southern part of the Monument has been treated in a report on the overlapping Zion Park region (Gregory, 1938) this chapter deals chiefly with the district northwest of Firepit Knoll and thus with the local characteristics of well-known, widespread stratigraphic units. The age, character, and thickness of the principal formations in the Zion National Monument are summarized in Table 1.

PERMIAN FORMATIONS

Rocks of Permian age, widespread and thick farther south, are exposed in Zion National Monument only in a narrow discontinuous band at the base of the Hurricane Cliffs between Deadman Hollow and the mouth of Spring Creek. Because of their general composition and their relation to the Triassic beds the outcrops along this stretch are assigned to the Kaibab formation, even though they lack certain features characteristic of typical sections.

In Deadman Hollow at the foot of a cliff that includes the basal member of the Moenkopi (Lower Triassic) formation the single bed of Kaibab that protrudes from the talus is dense cherty limestone. At Fall Creek more than 200 feet of Kaibab is displayed as dark-gray, resistant, massive, slightly arenaceous limestone, in beds 20 to 30 feet thick that contain fragmentary Permian fossils, exceptional amounts of disseminated chert, and long chert lenses 2 to 3 feet thick. North of Fall Creek for about 2 miles no identifiable Kaibab is exposed; it lies on the downthrown side of the Hurricane fault beneath talus and alluvium. At Locust and Wayne creeks outcrops of Kaibab consist of faulted and brecciated blue-gray limestone. At Camp Creek the formation is represented by two units: gray, massive, brecciated limestone 18 to 25 feet thick, in places about half chert; and above it, in contact with Triassic conglomerate, a dense, very hard bed of arenaceous, slightly cherty limestone 4 feet thick. At the mouth of Spring Creek Canyon 120 feet of irregularly bedded brecciated limestone was mapped as Kaibab.

Permian rocks are not shown on maps of the Wheeler or the Powell surveys. They seem first to have been recognized by Lee (1906), who "with some doubt" referred the massive limestone exposed at the base of the Hurricane Cliffs "5 miles south of Kanarraville" (Locust Canyon ?) to the Aubrey formation of the Carboniferous and correlated them with the Aubrey (Kaibab in part) in lower La Verkin Canyon, as defined by Huntington and Goldthwait (1904).

Fossils in the Kaibab are scarce, and most of them are fragmentary. J. B. Reeside, Jr., recognized the following forms: from Fall Creek, coral (undetermined), fenestelloid bryozoan (indeterminate), and *Productus* (*Buxtonia*) sp.—probably Permian; from Deadman Hollow, bryozoans of several sp. (undetermined), large round terebratuloid brachiopod (undetermined), crinoid columnal, fenestelloid bryozoan—Paleozoic fauna; from Spring Creek, *Plagioglypta canna* (White)—Permian, Uppermost Kaibab. The faunal evidence of Permian age of the rocks here classed as Kaibab is strengthened by regional comparisons; essential continuity of outcrops permits tracing of the beds southward into the abundantly fossiliferous topmost Kaibab in the Timpoweap Canyon of the Virgin River. The Kaibab formation in the Monument marks the top of the Permian and as generally elsewhere in southwestern

TABLE 1.—*Stratigraphic column of Zion National Monument, Utah*

System	Series	Group and formation	Lithologic character	Thickness (Feet)
Jurassic	Upper Jurassic	Entrada sandstone	Light-red, white-banded, fine; even-grained, thin-bedded, gypsiferous sandstone; very friable.	200+
		Carmel formation Unconformity	Bluish-gray limestone in resistant massive beds and soft shaly beds; a little argillaceous and gypsiferous shale; marine fossils; forms low cliffs and a bench on top of the Navajo sandstone.	450–560
	Middle Jurassic (?)	Navajo sandstone Unconformity (?)	Light-creamy-yellow, red-brown, and buff, highly cross-bedded sandstone; weathers in high cliffs and innumerable cones, towers, and domes; forms caves, alcoves, and natural bridges.	1300–1800
	Upper Triassic	Chinle formation	Red, brown, buff sandstones and subordinate limestone conglomerate particularly abundant near the top; near the middle a topographically prominent sandstone ledge (Springdale member); in lower half brightly variegated shales, sandstone, and conglomerate that weather as badlands and contain fossil wood and fish (Petrified Forest member); a series of slopes and cliffs.	1100–1350
Triassic	Upper Triassic	Shinarump conglomerate Unconformity	Light-gray to yellow coarse-grained to conglomeratic sandstone, very irregularly bedded; contains silicified wood; forms prominent ridges.	35–80
	Lower Triassic	Moenkopi formation Unconformity	Brown, red, yellowish, platy, thin-bedded, gypsiferous and calcareous sandstone; soft, pink and white, strongly gypsiferous band (Shnabkaib member) in upper half; fossiliferous marine limestone (Virgin member) in the middle; and limestone and conglomerate (Timpoweap member) at the base.	1080–1450
Carboniferous	Permian	Kaibab limestone	Blue-gray, white to yellowish massive, more or less dolomitic limestone, in part cherty.	0–200±

Utah unconformably underlies the Triassic. In most places the contact is marked not only by abrupt change in the composition, texture, and source of the materials, but also by a conglomerate of distinctive character—a feature of the Timpoweap member of the Lower Triassic Moenkopi formation.

TRIASSIC FORMATIONS

General features and relations.—Along the western side of the Monument between the Hurricane Cliffs and the vertical wall of red sandstone that projects from the rim of the Kolob Terrace, rocks of Triassic age are boldly outlined by color and topographic form. They comprise distinctive groups of gray, white, yellow, and red beds of conglomerate, sandstone, limestone, shales, and gypsum—all tilted at fairly high angles (Pl. 1, insert). In them erosion has developed a rough terrain of prominent hogback ridges and intervening subsequent valleys trending northward in harmony with the trend of the Kanarra fold (Pl. 8, fig. 1).

The Triassic here embraces three formations: the Moenkopi (Lower Triassic) and the Shinarump and the Chinle (Upper Triassic). In the Moenkopi six stratigraphic subdivisions are recognized of which two are unquestionably marine; the four others, possibly only three, show features characteristic of terrestrial sediments. The Shinarump and the four subdivisions of the Chinle are classed as nonmarine. As displayed in the Monument the lower boundary of the Triassic can be defined with reasonable accuracy as the base of the Moenkopi formation, but, though the Upper Triassic age of most of the Chinle seems established, there is doubt that the top of the Chinle as here defined is actually the top of the Triassic. As compared with the corresponding Triassic formations elsewhere in Utah, the Moenkopi of the Monument includes more limestone and gypsum; the Chinle contains less limestone and variegated shale and much more sandstone, particularly at the top where, with few shale partings, irregularly foliated and massive beds of fairly resistant sandstone total 800 feet in thickness.

Moenkopi formation.—In the Monument rocks assigned to the Moenkopi formation constitute a remarkably regular north-south belt about a mile wide paralleling the trend of the Hurricane fault. The formation is very conspicuous. In uptilted strata it appears as a series of broad parallel bands that from west to east are in turn dark gray, red, yellow, light gray, red, white, red. Small groups of adjoining beds distinguished by color and surface form may readily be traced across canyons, up slopes, over divides, down the sides of folds, and to abrupt terminations at faults. The lowermost band is a resistant ledge over which Taylor Creek, Locust Creek, and other streams descend as waterfalls; the middle band forms a continuous, sharply outlined ridge; and the topmost band a steep slope that terminates abruptly at the base of a persistent cliff.

In mass these major color bands and in detail minor bands of similar hue outline the erosion forms characteristic everywhere of the Moenkopi—flights of tiny steps in the thin sandstones, slopes and mounds in the gypsiferous shales, and low cliffs in the conglomerates and limestones. In places where a protecting cap of hard conglomerate or limestone is absent the soft shales have been intricately dissected into a maze of grooves and tiny canyons that wind in and out around ridges and tilted benches.

The maximum measured thickness of the Moenkopi in the Monument is 1452 feet, which is comparable with exposures in the Virgin River Valley and about four times the thickness of its type section in the Little Colorado valley, Ariziona. It also includes units represented only in southwestern Utah.

SUBDIVISIONS: Six groups or subdivisions of Moenkopi strata are recognized in the Monument. They are generalized lithologic and color units, not exclusive in composition; all of them include sandstone, shale, limestone, and gypsum, and all of them range widely in the amount and character of their constituent materials. The outstanding features of these subdivisions are generalized as follows (*See also* Sections 2, 3):

(1) Upper red member: Generally fine-grained, roughly stratified, shalelike sandstones and mudstones, light red, chocolate brown; cemented by lime and iron oxide; some gypsum and limestone; many beds ripple-marked; forms a steep slope. 150–350 feet.

(2) Shnabkaib member: White, pink, light-red, sandy, gypsiferous, friable shale and foliated gypsum; forms a rugged slope, brightly color-banded. 270–340 feet.

(3) Middle red member: Light-red and yellow-brown, shaly sandstones; dominantly fine, even quartz grains; some gypsum, generally thin, irregular bedding. 100–275 feet.

(4) Virginia limestone member: Blue-gray and gray-tan limestone; massive beds, 1 to 4 feet thick, and thin beds; includes paper-thin sheets of earthy calcareous shale; fossiliferous; forms a benched cliff. 115–130 feet.

(5) Lower red member: Light-red, streaked and dotted with white, mudstone and shaly sandstone; generally fine-grained; thinly and irregularly bedded; lenses of mud lumps; considerable gypsum; many lateral and vertical unconformities; on some beds ripple marks, sun cracks, and worm trails; forms steep slope. 200–370 feet (Pl. 5, fig. 3).

(6) Timpoweap member: Gray, coarse conglomerate (basal), gray-blue limestone, yellow, gray, and white sandy shale; forms steplike series of cliffs. 300–450 feet.

When closely examined, the upper, middle, and lower red members are substantially alike; they consist chiefly of well-worn quartz grains of small and medium size, bits of weathered feldspar, and a little biotite held together by calcareous, arenaceous, and ferruginous cement. They include also thin irregular sheets and secondary deposits of gypsum and lenses of a peculiar conglomerate made of limestone, mudstone, and claylike pebbles embedded in fine sand and recrystallized calcite. The Shnabkaib member includes as many as 30 gypsum beds grouped or separated by varying thicknesses of reddish calcareous, gypsiferous, quartzose shale. Many of its beds are fairly even and regular for as much as a mile; others are markedly lenticular. A few beds are massive, nearly pure selenite, as much as 4 feet thick, but most of them are measured in inches, and some are piled in sheets no thicker than cardboard.

In the Virgin limestone member the beds range from thick solid masses of nearly pure calcite (or dolomite ?) to friable, earthy, sandy calcareous shales. Tracing short distances along outcrops reveals gradual to rather abrupt change from one to another

style of bedding, texture, and composition. Few beds retain their individuality for as much as half a mile.

The Timpoweap member embraces a variety of rock types: Coarse conglomerate; limestone in thick, massive, and thinly foliated beds; and shales of various color and composition, some of them slightly petroliferous (sections 1, 2). Except in the conglomerate all the beds are fairly regular, contain much calcareous matter, and the same fossil fauna. An interesting feature of the Timpoweap is the presence of limestone pebbles containing Paleozoic fossils, presumably derived from the underlying Kaibab formation. In pebbles from Taylor and Fall creeks the following species were identified by John B. Reeside, Jr., as "probably Permian": fenestrelloid bryozoan; bryozoan, undetermined; crinoid columnal; productid brachiopods, fragments; *Puncto-spirifer* sp.

AGE: In the Moenkopi formation marine fossils are persistent features of the limestones, and from the "red beds" divisions a few bits of wood and bone have been obtained. In the lowermost limestones of the Timpoweap beds, pelecypods are generally present, and above the limestones, in all sections measured, the thinly laminated calcareous shales are richly fossiliferous; some beds consist almost entirely of shells tightly cemented by lime. In collections from the Timpoweap, John B. Reeside, Jr., recognized: *Pleurophorus?*, two species; *Myalina* sp.; *Monotis* sp.; *Pteria* sp. Fossils in the Virgin limestone member are fairly abundant, but most of them are internal molds difficult to determine. In a collection from Taylor Creek, Reeside identified *Pleurophorus?*, two species; *Myalina* sp.; *Nuculana?* sp., *Monotis* sp.; *Astartella?* sp.; and terebratuloid brachipods. All the species from the Moenkopi of the Monument are represented in the much larger faunas in the Timpoweap and the Virgin members at their type sections in the Virgin River Valley, and the strata in which they occur have a common stratigraphic position.

As determined by its fossil fauna the Moenkopi is Lower Triassic and the only formation of that age in southwestern Utah. Unconformably below it lies the Permian Kaibab formation and unconformably above it, the Upper Triassic Shinarump conglomerate. In places, however, the dividing plane between the Moenkopi and the Kaibab is obscure, and certain conglomerates near the contact may be either Triassic or Permian.

Shinarump conglomerate.—The Shinarump conglomerate in the Monument is conspicuous. Though less than 100, in most places less than 50, feet thick, it stands as a vertical gray cliff above steep red slopes and over large areas is the surface rock on the back slope of cuestalike ridges (Pl. 8, fig. 1). At all outcrops examined it displsys characteristic features—features outlined by Powell, Gilbert, and Dutton, and described in detail by many later students of the Colorado plateau province. It consists of masses of white, gray, and brown conglomerate, highly irregular beds of glistening quartz sandstone, thin short lenses of brown and red fine-grained sandstone, and varicolored arenaceous shale. It shows abrupt variation in texture and bedding, many lateral and vertical unconformities, and in places a seemingly haphazard distribution of component materials. Rough analyses show that quartzite and quartz constitute about 90 per cent of the pebbles more than 2 inches in diameter and 70 per cent of all pebbles and grains. Next in order rank pebbles of dense

limestone, chert, ironstone, and magnetite. Angular chunks, slabs, and logs of fossil wood are fairly abundant near the base.

Chinle formation.—The Chinle formation is continuously displayed in the area as a belt of brightly colored rocks between the prominent cliffs of gray conglomerate (Shinarump) and the more prominent cliffs of red sandstone (Navajo). The strata of this formation are tilted 5°–40° E., and in consequence the width of Chinle outcrops ranges, from about 2 miles at the mouth of Timber Creek to about half a mile where crossed by Camp and Spring creeks. Also, in consequence of tilting, the different beds are well exposed to weathering and stream abrasion; and the harder of them stand out as high cliff-bordered ridges and innumerable low angular ridges. The softer rocks form the floors of narrow gullies and somewhat broad swales. The resulting series of parallel ridges and gullies make up a rough surface. Travel that involves no difficult climbing is feasible only along the trend of the rocks, particularly along the crests of the ridges.

Viewed as a whole, the Chinle formation is a huge pile of coarse and fine, thick- and thin-bedded sandstones of various shades of red; but it includes varicolored conglomerates; limestones; argillaceous, gypsiferous, and calcareous shales; siltstones; and volcanic ash—an assemblage remarkable for vividness and variety of color. This wide range in character of component materials and in coloring is matched by the range in style of bedding. The thicknesses and relative positions of individual sandstone, limestone, and shale beds and groups of beds are different in each measured section. Some beds, particularly those near the top of the formation, retain their characteristic features for as much as a mile, but most of them change noticeably within shorter distances; in fact, many beds in the lower half of the formation are merely thin, narrow lenses which appear and disappear within a few feet. In five measured sections the total thickness of the Chinle ranges from 1200 to 1370 feet and is thus comparable with its maximum thickness (1380 feet) in the neighboring Zion Park region but greater than at most other places in Utah.

The few fossils found in the Chinle of the Monument—not yet identified—doubtless are species found elsewhere in the formation. In any event, the exposures of Chinle in the area are continuous with those in the Zion Park region and can be traced southeastward across Utah to the type section in Arizona. At many widely separated places, fossil wood, saurian bones and tracks, and impressions of fish date the Chinle as Triassic, very probably Upper Triassic.

Though the Chinle formation in mass is easily recognized, its boundaries are not well established. At the base of the formation no clearly defined features mark the contact of the Shinarump conglomerate and the Chinle sandstone. Likewise the contact between the bedded Chinle sandstones (Triassic) and the massive Navajo sandstone (Jurassic ?) above can be but tentatively drawn (Pl. 6, fig. 2).

SUBDIVISIONS: As seen from almost any high point within the Monument, the Chinle comprises three groups of strata, characterized by diverse topographic form and, to a considerable degree, by color. Closer examination of the composition, texture, and arrangement of the strata, however, permits the recognition of four subdivisions, (Section 1, 2).

(1) Upper sandstones: Sandstone light- to dark-red, white streaked, fine- to

medium-grained in roughly regular beds 1 to 10 feet thick; stratified with very thin sandy shale beds in groups 2 to 5 feet thick; includes lenses of laminated and conglomeratic limestones; beds in lower part ripple-marked. Forms vertical ledges and steep slopes. 500–800 feet (Pl. 8).

(2) Springdale sandstone member: Sandstone, light-red streaked with white; indistinct lenticular beds 2 to 10 feet thick, separated in places by very thin layers of imbricated shale; includes pellets of concretionary limestone and clay; ripple marks common. Forms a vertical cliff on a prominent ridge. 40 to 180 feet (Pl. 5, fig. 2).

(3) Petrified forest member: Upper part light-red and brown, irregularly bedded sandstones and sandy, argillaceous, carbonaceous, and calcareous shales widely variable in composition; lower part brilliantly variegated, friable shales of various composition and degrees of hardness, which weather into bad-land forms; contains much fossil wood. Forms broken slopes and valley floors. 300–400 feet.

(4) Lower sandstone: Sandstone gray, dark-brown, and purple, in lumpy uneven resistant beds; many concretions of sand, and ironstone, and fragments of petrified wood. Forms lumpy surface. 20–60 feet.

JURASSIC FORMATIONS

General features.—Elsewhere in the plateau country the Jurassic generally consists of three major subdivisions: the Glen Canyon group, comprising the Wingate sandstone, the Kayenta formation, and the Navajo sandstone; the San Rafael group which includes the Carmel formation, the Entrada sandstone, the Curtis formation, and the Summerville formation; and the Morrison formation (in its absence, the Winsor formation). In the Monument the Glen Canyon group is represented only by the Navajo sandstone, and the San Rafael group only by the Carmel and Entrada formations. Jurassic formations younger than the Entrada have been removed by erosion. Consequently the three lines of great cliffs that mark the position of the Morrison formation, and the long intervening slopes and benches that give distinction to many landscapes elsewhere in Utah and Arizona, are replaced in the Monument by s single cliff composed of Navajo sandstone. The usual stairlike profile of walls set on sloping bases is absent; one towering wall is followed downward by a slope (Pl. 6, fig. 1).

Navajo sandstone—Of all the rocks in the area, the Navajo sandstone seems to have attracted the most attention. Nearly 60 years ago Dutton (1882) called attention to the spectacular topography of the "Jurassic sandstone" along the front of the Kolob Terrace and pictured the erosion forms in two famous sketches: *A midsummer day's dream on the Colob* and *Jurassic Terrace—the Colob.* In more recent years the few map makers, scientists, and hardy tourists who have visited Hop Valley, La Verkin Valley, and the headwater branches of Taylor, Camp, and Timber creeks have spoken enthusiastically of the gorges, cliffs, and mesas carved from the Navajo sandstone. To the geologist interest is enhanced by the knowledge that the Navajo in the Monument is but a part of the great sandstone bed that, extending eastward across Utah and northeastern Arizona into southwestern Colorado, forms magnificent escarpments, isolated towers, and the walls of deep canyons, in many places decorated by natural bridges, arches, and cliff caves—the home sites of a vanished race. Over

FIGURE 1. TUCUPIT POINT, SPUR OF NAVAJO SANDSTONE (Jn) PROJECTING FROM RIM OF KOLOB TERRACE Between Middle and North forks of Taylor Creek. Talus-covered Chinle formation (Trc) (lower right); Carmel formation (Jc) (upper left). Height above canyon floor 1800 feet.

FIGURE 2. SHUNTUVI, SOUTHWEST TERMINUS OF TIMBER TOP MESA
Chinle (red and white banded resistant sandstone) in contact with Navajo (bedded at base, massive above). Wingate and Kayenta are lacking. Vertical distance shown, 1600 feet.

FEATURES OF THE NAVAJO AND CHINLE FORMATIONS

FIGURE 1. FIREPIT KNOLL (a) AND SPENDLOVE KNOLL (b)
Basaltic cones of very recent age, typical features of the Kolob volcanic field. Kolob Terrace (upper middle) bounded by walls of Navajo sandstone over which lava streams descend; Markagunt Plateau (skyline).

FIGURE 2. PART OF KOLOB VOLCANIC FIELD
Looking southeast across canyons of Virgin River to Moccasin Terrace (skyline). Lava (foreground) has buried the rough topography developed in sedimentary rocks. Above it rises the islandlike Pine Valley Peak (upper right) and towers of Zion National Park (upper left).

VOLCANIC FEATURES

its exposure of about 40,000 square miles the Navajo sandstone differs little in composition and texture, and in material respects descriptions of its outcrops on the Navajo Indian Reservation (its type locality), the Kaiparowits Plateau, and in Zion National Park apply almost equally well to those in the Zion National Monument. A notable difference is its general color: in eastern Utah red; in south-central Utah white (the White Cliffs); in Zion Park red at the base, white in the upper half (the Great White Throne); in Zion Monument, entirely red.

In the Monument the Navajo sandstone is pre-eminently the cliff maker. Though slightly tilted it develops erosion features like those in horizontal rocks of uniform composition. Its edges are sharply cut off, and its surface weathers into mounds, domes, ridges, and smoothly outlines spires. In canyons and on projecting buttresses where it is fully exposed, it ranges from 1500 to 1800 feet thick, the difference due at least in part to the uncertainty in placing its base. In some views the sheer walls seem even higher because they are cut from top to bottom by vertical joints, in places by prominent rifts that widen upward into grooves (Pls. 2, 8).

The outstanding lithologic features of the Navajo sandstone are general uniformity of grain, cross-bedding, and massiveness. In most places, however thick, it is one homogeneous, indivisible stratum composed chiefly of round grains of translucent quartz averaging about 0.15 millimeter in diameter, cemented by iron and lime. Minerals other than quartz are sparsely included, also thin lenses of limestone, shales, and concretionary mudstone. Cross-bedding is universal and remarkably variable. Some laminae appear as groups of parallel straight lines in vertical, horizontal, or oblique position; others are curved, still others wrinkled, some are grouped as wedges. However, as compared with its exposure in Zion National Park and in the cliffs east of the Parunuweap Valley, the Navajo in the Monument is less persistently massive, and its cross-bedding less elaborate. In places its lower part is stratified, and cross-bedding laminae are inconspicuous.

No diagnostic fossils have been found in the Navajo of Zion Monument, and its age is therefore uncertain. However, as the sandstone overlies the Chinle formation of Triassic age and underlies the Carmel formation of Upper Jurassic age, it is classed tentatively as middle Jurassic.

Carmel formation.—Overlying the Navajo sandstone is the Carmel formation—essentially a group of limestone beds containing marine fossils. Though in most places less than 500 feet thick, it is a resistant formation in the midst of friable beds and therefore assumes prominence in the topography. In the northeastern part of the Monument the Carmel forms the surface from which soft overlying sediments have been stripped and into which have been cut deep canyons. Farther west it is the cap rock for such mesalike outliers as Burnt Mountain, Nagunt Mesa, and Timber Top. In the rocks that inclose the box-headed canyons it is the top layer; in fact, the preservation of the titanic walls in La Verkin, Timber, and Taylor valleys and the vertical cliffs about the base of Horse Ranch Mountain is due to the protective ledge of the Carmel formation.

Most of the beds of the Carmel formation are thin and regularly stratified and range from hard, masive, nearly pure limestone to calcareous shales (Section 2). Wherever examined the formation includes lenses and in places thick sheets of limestone breccia more resistant than the normal rock.

The Carmel formation contains a fauna characteristic of early Upper Jurassic time. In collections from Horse Ranch Mountain, John B. Reeside, Jr., recognized *Pentacrinus asteriscus* Meek and Hayden, *Ostrea engelmanni* Meek, *Ostrea stringilecula* White, and *Camptonectes stygius* White, and *Lima* n. sp.

Entrada sandstone.—The highest and youngest consolidated sedimentary rocks in the Zion National Monument is the Entrada sandstone. It is exposed on the flanks of Horse Ranch Mountain where it forms a slope extending from the topmost limestone beds of the Carmel formation to the capping sheets of basalt. On this slope the rock is so disintegrated that satisfactory examination of bedding, texture, and composition is impracticable. However, talus fragments and small outcrops show the major features characteristic of the Entrada elsewhere in Utah; evenly stratified red and white banded sandstones, generally gypsiferous and in part calcareous. Though overlying beds are absent, the stratigraphic position of the formation seems in no way uncertain. A few miles east of Horse Ranch Mountain equivalent strata lie between the Carmel and the Curtis formations, both of demonstrated Upper Jurassic age.

SECTION 1.—CANYON OF CAMP CREEK

Bed No.	*Description*	*Thickness (Feet)*
	Navajo sandstone	
	Chinle formation	
28	Sandstone; sandy, argillaceous and calcareous, variegated shales; calcareous conglomerates; some volcanic ash (?); petrified wood and rare fossil bones; largely covered by talus and debris of landslides; Springdale member forms a prominent hogback; thickness estimated	1200
	Shinarump conglomerate	
27	Conglomerate and sandstone; mostly glistening coarse angular grains of quartz sand; rounded pebbles of quartzite, quartz, black limestone, and metamorphic rock 1 to 4 inches in diameter isolated or grouped in short thick lenses; petrified wood at the base	35–45
	Unconformity	
	Moenkopi formation	
	Upper red beds	
26	Sandstone, light-red, massive, fine-grained, fairly regular beds	15
25	Shale, sandstone, and mudstone, red; alternating thin beds; stratification fairly regular; quartz grains cemented by iron and lime; some gypsum; few lenses of limestone and of dark sandstone impregnated with iron	121
24	Sandstone, red; massive beds, in places crossbedded	20
	Total upper red beds	156
	Shinabkaib member	
23	Sandstone and sandy shales, red and white; soft, gypsiferous; gypsiferous mud stones; green-white gypsum in thin wrinkled beds, veins and isolated aggregates; few lenses of limestone, mud shales and oolite; forms a conspicuous deeply weathered red slope crossed by 9 bands of white	338
	Middle red beds	
22	Shales, sandy, and sandstones, light-red; beds 2 inches to 4 feet thick; generally fine even quartz grains cemented by lime and iron; rare mica; soft; forms slope largely covered with disintegration products	132

	Virgin limestone member	
21	Sandstone, white; calcareous; includes lumps of clay and lime concretions	4
20	Shale, red; sandy	4
19	Shale, gray; gypsiferous; minutely foliated	12
18	Limestone, red; irregular shale-like beds	10
17	Shale, brown; regularly bedded; dense; breaks in hard splinters	6
16	Shale, gray; sandy	7
15	Shale, tan; hard; thinly, evenly bedded	5
14	Limestone (?), shaly ?, earthy ?, slope covered	20
13	Limestone, gray; three regular beds separated by calcareous shale	10
12	Shale, gray, calcareous	4
11	Limestone like no. 8	13
10a	Shale, gray, irregular, crinkled beds, strongly calcareous	5
10	Limestone, gray, dark-blue on fresh surfaces; beds 6 inches to 2 feet thick; firmly compacted; fossiliferous; includes paper thin sheets of brown shale and lenses of earthy arenaceous limestone	10
	Total Virgin limestone member	115

(Nos. 8–11 together form a cliff that stands as a conspicuous hogback on the dip slope of the Kanarra fold.)

Unconformity ?

	Lower red beds	
9	Sandstone, shale, and mudstone; generally red-streaked and dotted with white; beds 2 to 12 inches thick; many beds lenticular, some imbricated; disseminated gypsum; many lateral unconformities	136
8	Sandstone, shaly, white; includes gypsum in layers, veins, and cement	15
7	Like no. 9	108
	Total lower red beds	259
	Timpoweap member	
6	Sandstone, yellow and white; beds 1 to 8 inches thick; some beds pure fine-grained quartz cemented with lime and iron, others gypsiferous or calcareous; the more compact beds show glistening ripple marked surfaces and break into hard blocks; flattened mud lumps common; forms a steep uneven slope	40
5	Limestone, gray to brown; sandy; in regular beds, $\frac{1}{16}$ inch to 3 inches thick; Triassic fossils abundant	15
4	Shale, yellow; calcareous and furruginous; minutely fine-grained, evenly stratified; forms a gentle slope	47
3	Limestone, gray-blue; in roughly defined beds 1 to 3 feet thick; generally arenaceous; includes near the base lenses of coarse-grained sandstones and scattered pebbles of quartzite and chert; sparsely fossiliferous; forms wall with vertical steps; thickness estimated	250

Unconformity

2	Conglomerate; chiefly coarse-grained sandstone and subangular and rounded pebbles of chert, pure quartz, quartzite and blue limestone, $\frac{1}{4}$ to 3 inches in diameter, average about $\frac{1}{2}$ inch; forms wall; thickness estimated	100
	Total Timpoweap member	452
	Total Moenkopi formation	1452

Unconformity

Bed No.	Description	Thickness (Feet)
	Kaibab formation	
1	Limestone, gray; a dense, hard, uneven bed; some chert	4
	Limestone, gray, massive, brecciated; includes much chert, in places about half the rock; unfossiliferous ?; broken by Hurricane fault; thickness exposed	30
	Total Kaibab formation	34+

SECTION 2.—TAYLOR CREEK

From face of Hurricane Cliffs to summit of Horse Ranch Mountain
Dip 5–40° E.

Bed No.	Description	Thickness (Feet)
	Basalt	
	Entrada sandstone	
	Completely disintegrated	200+
	Carmel formation	
56	Limestone, gray and brownish-gray; very thin shingle-like beds	8
55	Limestone, gray to cream; alternating beds of thin shaly and thick massive limestones; thicker beds arenaceous	6
54	Limestone, blue-gray, weathering to white; massive, pure; contains abundant Jurassic fossils	5
53	Limestone, gray to white; very massive; no interbedded shale; slightly arenaceous in places	37
52	Limestone, gray to almost white; thin-bedded; dense, very pure; contains numerous lenses of breccia as in no. 51, and a few beds 2 to 4 inches thick of slightly arenaceous limestone	74
51	Limestone breccia; mainly angular fragments of massive and thin-bedded limestone a fraction of an inch to 18 inches in largest diameter, cemented with a pure blue-gray limestone; forms a prominent ledge	53
50	Limestone, blue-gray; dense; breaks into hard, angular fragments	32
49	Limestone like no. 48 but thinner-bedded and less fossiliferous	11
48	Limestone, light-gray, weathering to brown; very arenaceous; well stratified, but difficult to cleave along bedding planes; ripple marks common on talus slabs measure 2 to 4 inches from crest to crest; abundantly fossiliferous; a very prominent ledge, continuous for 1000+ feet	10
47	Limestone, buff to gray; beds 4 to 12 inches thick, separated by thin layers of calcareous shale; upper part richly fossiliferous, in places resembling coquina	59
46	Limestone, gray, weathering to dirty white; very dense and pure; beds 8 to 12 inches thick, separated by a few thinner beds	57
45	Limestone, gray; alternating layers 4 to 18 inches thick	7
44	Limestone, gray; hard; extremely thin bedded; a few small outcrops on a talus covered slope	195
	Total Carmel formation	554

Unconformity

Bed No.	Description	Thickness (Feet)
	Navajo sandstone	
43	Sandstone, red from bottom to top, massive, cross-bedded on large and small scale; parting planes especially near the base; forms vertical wall; thickness estimated	1500+

Unconformity ?

Chinle formation

Upper sandstone member

42	Sandstone, light-red; roughly regular beds; weathers as rounded ledges separated by grooves, forms a steep slope at the base of no. 43; estimated average thickness.	80
41	Sandstone, light- to dark-red, crossed by a few white bands; beds 3 inches to 5 feet thick; fine-grained; includes thin lenses of laminated limestone and white corrugated shale	560
40	Sandstone, light-red; layers thin as cardboard combine to make beds 1 to 4 inches thick and more massive irregular beds, 2 to 5 feet thick; the two types of bed separated by evenly laminated, slightly sandy ripple-marked mud shale; weathers to hard chips and angular blocks; forms a steep cliff. Thickness estimated	120

Springdale member

39	Sandstone, white streaked with red; indistinct beds 3 to 8 feet thick, divided into paper-thin layers and separated by thin sheets of greenish, imbricated, ripple-marked shale; grains in the sandstone subangular quartz (95 per cent), clay, concretionary limestone, garnet (?), and muscovite less than 0.1 millimeter in diameter; hard, tightly cemented by clay and lime. Forms a prominent vertical cliff traceable for at least 2 miles; average of measurements in three places	41
38	Sandstone, light-red; exposed beds fine-grained, thinly, evenly laminated, many of them ripple-marked; cement chiefly lime; forms a steep slope largely covered by talus from nos. 39 and 40	136
	Total Springdale member	177

(The measurements of beds 38–41 inclusive were made at widely spaced outcrops on slopes largely covered with talus in an area where dips are irregularly variable. The error may be more than 100 feet.)

37	Sandstone, light-red, sparingly banded with white; lenticularly bedded; fine grains of quartz cemented by lime and iron oxide; includes thin, short sheets and irregular masses of gray and red mud shale, some of them lignitic, which on weathering leave grooves and pits; in places forms a strong cliff of seemingly massive rock but generally along strike is shaly like no. 36	34

Beds like no. 37 were not recognized in other sections measured in the Zion National Monument.

Petrified Forest member

36	Shale, light-red, sandy, irregular beds that include lozenges and flakes of gray mud shale and carbonaceous material; only lower 27 feet exposed	65
35	Shales, sandy, and thin sandstone; light-red; unevenly bedded; generally fine-grained; includes a bed 4 feet thick and two thinner lenticular beds of bone-bearing limestone conglomerate	22
34	Like no. 31	51
33	Sandstone, dark-brown, dense; consists chiefly of quartz, black mica, and iron oxide; a resistant ledge replaced along strike by coarse-grained white sandstone	7
32	Sandstone, white; fine-grained; massive; calcareous; a ledge maker	2
31	Shales, sandstones, and limestones, extremely irregular in thickness, composition, and continuity of bedding; bands, patches, and dots colored white, gray, red, purple, and black; includes quartzose, micaceous, calcareous, gypsiferous, and ferruginous sandstones; thin regular sheets, nodules, and conglomeratic masses of varicolored limestone, clay, volcanic debris, and lignitic material; fragments of vertebrate bones appear in the conglomerates, fish skeletons in the clays, and, especially near the base, petrified wood is common. Forms a brightly colored slope that at a distance has the appearance of weathered marls	219
	Total Petrified Forest	366

	Lower sandstone member	
30	Sandstone, gray, in places purple; overlapping beds ½ to 2 feet in thickness; unevenly distributed grains of quartz, mica, magnetite, and hornblende (?), tightly cemented with gypsum, iron, and lime; average thickness 200 feet along strike	15
29	Sandstone, dark-brown, in highly lenticular, lumpy beds that include aggregates of drab clay shale; fine and coarse grains cemented by iron oxide and lime; contains many ironstone concretions which on weathering strew the slope with hard black sand balls 3–8 inches in diameter; thickness along strike 0–12 feet	7
	Total Chinle	1359
	Shinarump conglomerate	
28	Conglomerate; rounded and subangular, pebbles chiefly quartzite, quartz, chert, and ironstone 1 to 3 inches in diameter, arranged thin and thick, long and short overlapping lenses, in strings, and isolated; upper part essentially coarse gritty sandstone, includes chunks and logs of petrified wood; forms cliff	60–80
	Unconformity	
	Moenkopi formation	
	Upper red beds	
27	Shale and thin sandstones, red-brown; even-bedded; fine-grained, many beds ripple-marked; forms a steep slope	237
26	Sandstone, light-red in two massive beds; fine-grained, imbricated	16
25	Shale, red, brown, and white; sandy; fine-grained; thin-bedded, alternating and interleaved with beds of gray, medium-grained sandstone; along strike appears as a prominent ledge	22
24	Shale, red, very sandy, generally in regular beds, includes sheets and lenses of hard sandstone	80
	Total upper red beds	355
	Shinabkaib member	
23	Shale, red, pink, chocolate, white; fine-grained, sandy, slightly gypsiferous, friable, alternating with unevenly spaced bands of gray-green, highly gypsiferous, ripple-marked shale; white calcareous bands near base and top; gypsum abundant in thin beds, seams and isolated aggregates, especially conspicuous 100 to 200 feet from the base; forms a steep slope, largely covered; thickness estimated	275
	Middle red beds	
22	Shale, red; thinly unevenly bedded; crossed by two bands of gray-green sandstone; gypsiferous	46
21	Sandstone, red; hard	6
20	Shale, light-red; sandy	16
19	Sandstone, red, parts of it gray-green; fine-grained; thin-bedded; resistant; projects as a shelf	4
18	Shale, chocolate-brown; regular thick and thin units; red, flaky, irregularly bedded at base; forms a slope	30
	Total middle red beds	102
	Virgin limestone member	
17	Shale, gray; sandy, highly calcareous; grades along strike into dense massive limestone; includes lenses of red and gray earthy material	22
16	Limestone, massive; ledge maker	3
15	Limestone, shaly; earthy	12
14	Limestone, sandy, in thin, hard beds	5

13	Limestone and calcareous shales	16
12	Limestone, single massive bed	4
11	Shale, gray-tan; highly calcareous; along strike changes to thick compact beds; in places earthy and slightly conglomeratic	27
10	Limestone, blue-gray; firmly compacted, resistant beds 1 to 3 feet thick; crushed fossils abundant; includes ball-like aggregates of malachite. (Nos. 10–16 form cliffs separated by steep slopes and in the topography are combined in a prominent hogback.)	30
	Total Virgin limestone member	119

Unconformity

Lower red beds

9	Shale and thin-bedded sandstone, light-red (lower 10 feet dark-red), in places nearly black and crossed by lenses of greenish-white sandstone; generally fine-grained; at a distance composition seems uniform and bedding regular; nearby many beds seem to consist of tiny overlapping flakes, lenses, and lumps; coarse- and fine-grained; includes gypsum as tiny lenses, seams, and cement; alkali seeps at the base; forms a steep, furrowed slope; thickness (in part estimated)	290
8	Sandstone, gray; thin slablike beds; coarser-grained than no. 6; thin basal beds of green shale	8
7	Shale, red, sandy	37
6	Sandstone, red; thin irregular beds; very fine-grained; gypsiferous and calcareous cement, includes beds 5 feet thick of green-gray, gypsiferous sandstone	42
	Total lower red beds	377

Timpoweap member

5	Shale, dark brown, sandy, interbedded with green-gray gypsiferous sandstone; includes seams and lenses of gypsum and thin sheets of hard, compact, imbricated sandstone that breaks into blocks; in places coated with alkali bloom	12–29
4	Shale, red, yellow, purple; friable; essentially consolidated sandy mud arranged in layers and lumpy aggregates; includes thin calcareous lenses rich in fragmental shells	6
3	Shale, yellowish; thin regular beds, ripple-marked, fossiliferous; thickness 1 to 5 feet	3
2	Limestone, gray, arenaceous; uneven beds 3 inches to 3 feet thick, in places slabby; alternating or interchanging along strike with hard blue-gray limestone and lenses of fine-grained conglomerate; topmost layers limestone, in thin, regular beds, slightly bituminous and fossiliferous	38
1	Conglomerate, gray; pebbles of chert 90 per cent quartzite, quartz, and black limestone ½ to 3 inches (a few more than 6 inches) in diameter; most pebbles rounded, some minutely fractured; held together chiefly by gray, oily-looking fragmental limestone and comminuted chert; ultimate cement, lime; some pebbles include fragmentary crinoids, pelecypods and productids; lower part coarser and more calcareous; upper part includes thin, short lenses of sandy limestone. Forms steep walls	130
	Bed of stream	
	Lowest rocks exposed	
	Total Timpoweap	206
	Total Moenkopi	1080
	Total section measured	4773+

SECTION 3.—DEADMAN HOLLOW
Dip sedimentary rocks 15–40° NE.

Bed No.	Description	Thickness (Feet)
	Basalt	
	Unconformity	
	Shinarump conglomerate	
	Unconformity	
	Moenkopi formation	
	Upper red beds	
19	Shale and subordinate sandstones, red, red-brown, a few white beds; dominantly well rounded quartz grains cemented by ferruginous clay and calcite; some disseminated gypsum. Shales, sandy, fine-grained, generally even-bedded but in places interleaved with massive sandstone as much as 4 feet thick; some beds ripple-marked. Sandstones in massive beds 2 to 8 feet thick, fine-grained, imbricated, some cross-bedded; forms a steep slope	147
	Shnabkaib member	
18	Shale, red, pink, chocolate-colored; sandy, friable, irregularly alternating with cream and green-white strongly gypsiferous mud shales, in many places ripple-marked; gypsum abundant as thin beds, seams, and scattered aggregates; disintegrates readily; forms a conspicuous color-banded slope	293
	Middle red beds	
17	Essentially like nos. 7 and 13	275
	Virgin limestone member	
16	Gypsum, green-white; sandy; very thin wavy beds	2
15	Sandstone, gray; shaly; gypsiferous cement	8
14	Gypsum, like no. 16	2
13	Shale, red; irregularly, thinly bedded; includes veinlets of gypsum	14
12	Sandstone, green-white, gypsiferous	3
11	Sandstone, red; thin hard beds; calcareous	17
10	Limestone, drab, massive in beds about 1 foot thick	15
9	Shales, gray and dark blue; in regular beds as thin as cardboard; highly calcareous; includes three beds of massive limestone 6± inches thick	30
8	Limestone, gray-blue; beds 3 inches to 3 feet thick separated by very thin-bedded calcareous shale; surfaces rippled and marked by shallow cuplike depressions; fossiliferous; poorly exposed	35
	(Nos. 8–10 are cliff makers and together form a prominent hogback.)	
	Total Virgin member	126
	Unconformity	
	Lower red beds	
7	Shale and shalelike sandstones, light-red, in places spotted and streaked with white; dominantly fine quartz grains cemeted by iron and lime; includes gypsum in tiny lenses, seams, and cement; many lateral and vertical unconformities; some beds consist of overlapping flakes and lumps, coarse- and fine-grained; many beds show ripple marks, sun cracks, and worm trails	196
	Timpoweap member	
6	Limestone, blue-gray and sandy shale, yellow; beds average less than 2 inches thick; richly fossiliferous	87
5	Limestone, gray; regular thin beds; dense, resistant, contains many veins of secondary calcite	114

4	Sandstone and sandy shale, yellow; calcareous; includes small aggregates of limonite and calcite	8
3	Limestone, gray; thin-bedded; hard; fossiliferous	35
2	Limestone, gray; massive in beds 3 to 6 feet thick; in places brecciated; contains isolated chert and quartzite pebbles, also Triassic fossils; resistant; forms prominent bench on a steep slope	106
1	Conglomerate, dark gray; rounded pebbles of chert, limestone, quartz up to 3 inches in diameter; lenses of coarse sandstone; matrix of dense limestone; some limestone pebbles contain fossils characteristic of the Kaibab formation	35
	Total Moenkopi	1422

(In the topography of the Timpoweap member nos. 1–6 stand as stepped ledges and in near-by places form the basal wall of Hurricane Cliffs.)

Kaibab formation (?)

Concealed by coarse gravel.

IGNEOUS ROCKS

In the Zion National Monument, igneous rocks are represented by volcanic cones and by streams and isolated patches of lava. No dikes or other intrusives are known. All the igneous exposures are topographically prominent, and most of them easy of access. Along the western side of the Monument at Black Ridge and Pace Knoll lava sheets lie at the top of the Hurricane Cliffs; their frayed edges stand as black walls above a slope of red and white rocks. Near the northern edge of the Monument, lavas thickly coat the top and the upper flanks of Horse Ranch Mountain. The southern extension of the Monument is so fully covered by lava streams and cones as to deserve recognition as the Kolob volcanic field. Within an area of about 20 square miles south and east of Jobs Head, more than half the surface rock is lava, and from favorable viewpoints the landscape suggests a sea of lava from which rise islandlike ridges and domes of sandstone (Pl. 7). Successive flows from such lofty craters as Firepit Knoll, Spendlove Knoll, and Home Valley Knoll, and from less conspicuous sources, have spread widely over flat lands and filled valleys to depths of 15 to more than 100 feet. Continuous streams of lava extend for about 9 miles down Grapevine Wash and along North Creek Valley and 4 to 6 miles down Pine and Pine Springs valleys. Farther south lavas from the prominent Crater Hill extend into Coalpits Wash.

Though the igneous rocks in the Monument range widely in texture, their composition is essentially the same, and all are olivine basalt. The chief minerals of the dense and amygdaloidal lavas, of the lapilli, and the ash are labradorite, olivine, magnetite, and augite in a granular groundmass of plagioclase and augite.

The volcanics are the youngest consolidated rocks in the Zion Monument; they postdate the profound regional erosion that produced the Kolob Terrace and established the major lines of drainage. Even such remnant lava masses as Black Ridge and Pace Knoll, which now occupy highlands, rest on gravel suggestive of former stream beds. The lavas lie indifferently on horizontal and tilted Triassic and Jurassic sandstones, limestones, and shales. In North Creek Valley, at Pace Knoll, and at Crater Hill they rest on the Monenkopi and the Shinarump formations; at Black Ridge, on the Shinarump conglomerate and the Chinle; in Pine Springs Valley, on

the Chinle; in Cave Valley, on the Navajo sandstone; and at Horse Ranch Mountain, on the Entrada sandstone. Evidence that latest volcanic activity followed the development of the present topography is the relation of lava flows to valleys. The outpouring lavas have utilized the valleys as ready-made runways, faithfully following their meandering courses. In places they have poured over cliffs. In Cave Valley, Lee Valley, and in large areas northeast of Pocket Mesa there was sufficient lava to obliterate the old drainage channels and to necessitate the establishment of new ones around and across the flows. Some streams of lava, especially along their lower stretches, only partly filled their chosen valley and thus allowed the pre-existing streams of water to maintain their general courses after minor readjustment.

In the absence of stratigraphic time markers more recent than the Entrada sandstone (Upper Jurassic), the age of the cones and flows can not be satisfactorily determined. The approximate date of regional volcanism, however, can be fixed with reference to faults and cycles of erosion, and the relative dates of eruption at various localities can be established by rough estimates of the amount and rapidity of erosion. Thus the lavas at Black Ridge at an altitude of 6500 feet appear to be parts of sheets that find their counterparts in Ash Creek Valley about 1600 feet below. The displacement was caused by the latest movements along the Hurricane fault, believed to have occurred in early Quaternary time. That the remnant lava flows along the crest of Hurricane Cliffs are relatively old is also shown by their form, position, and degree of weathering. Pace Knoll and Black Ridge are doubtless parts of once-continuous sheets of lava which have been largely stripped away. In contrast with these faulted and much-eroded remnants, most of the lavas in the Kolob volcanic field are remarkably fresh—even those that record intermittent eruptions. In form and structure some of the lava streams are so like those from volcanoes now active that it is difficult to think of them as more than a few centuries old. They retain their slaggy surface, roughened by broken blocks, and other irregularities produced by lateral pressure and by gas expansion. The cones, typified by Firepit Knoll, likewise seem youthful. Their outer slopes are normal for fragmental materials piled about volcanic vets, and their summit craters have characteristic form. Both inner and outer slopes are strewn with lapilli, bombs, and broken slabs of dense and scoriaceous basalt. Since they were formed, however, rain wash has gullied the slopes of cones and partly filled the craters, and streams have cut little canyons in the lava flows.

STRUCTURE

REGIONAL FEATURES

The Zion National Monument is the west-central edge of the great earth block between the Hurricane and Sevier faults and extends from the Colorado River northward to central Utah. East and south of the Monument the strata are horizontal or gently inclined except where interrupted by low folds and by faults of small dispalcement. Within the Monument all the strata have been much disturbed. The chief structural features are the prevailing high inclination of the strata, three

FIGURE 1. EASTWARD-DIPPING STRATA IN KANARRA FOLD BETWEEN LOCUST AND TAYLOR CREEKS
Shnabkaib and upper red members of the Moenkopi formation (Trm) (left); Shinarump conglomerate (Trs) (first ridge); Petrified Forest member (bench) and upper sandstones (base of cliffs) of the Chinle formation (Trc); Navajo sandstone (cliffs).

FIGURE 2. HURRICANE CLIFFS
Looking north across mouths of Wayne and Camp canyons. Escarpment of Kaibab formation (Ck), and Timpoweap member (Trmt) of Moenkopi formation represents upthrown block of Hurricane fault; alluvial fans thickly cover downthrown block.

STRUCTURAL FEATURES

faults (Hurricane, Bear Trap, and Cougar Mountain), and the Kanarra fold. The strata also exhibit low, broad folds, especially noticeable in the walls of canyons; sharply marked wrinkles, most of them monoclinal and involving several beds; and distortions confined to single beds. Prominent joints, singly and in groups, characterize the thick beds of sandstone and limestone, and many of them have been converted into faults with small throws—rarely more than a foot.

The sedimentary rocks dip northeastward (north, northeast, and east) (Pl. 1 (insert); Pl. 8, fig. 1); only the lavas are not conspicuously tilted. Along the Hurricane Cliffs the dips in most places measure 20°–80°, a few 90°. East of the Hurricane Cliffs the dips decrease, in some places abruptly, in others gradually, until in the upper La Verkin canyons dips of more than 2° are exceptional. South of Jobs Head and Firepit Knoll, dips of 2°, 1½°, 1°, and ½° are representative.

HURRICANE FAULT

Next to the prevailing tilt of the strata the outstanding feature of the regional structure is the Hurricane fault—a master belt of displacement in the plateau country of Utah and Arizona. Throughout its length of approximately 200 miles, from the Aubrey Cliffs south of the Colorado River to the base of the Tushar Mountains in west-central Utah, movements along the Hurricane fault have profoundly disturbed the sedimentary and igneous rocks and remodeled the topography by bringing high plateaus in abrupt contact with broad expanses of lowland. In Utah, this great zone of dislocation marks the position of the lofty Hurricane Cliffs which divide the belt of farms and orchards about Hurricane, La Verkin, Toquerville, Midway, Kanarraville, Fort Hamilton, Cedar City, Summit, Parowan, and Paragonah from the uninhabited, high-lying grazing lands of the Little Creek Terrace, Kolob Terrace, and the Markagunt Plateau. Naturally, a feature of such geologic and geographic prominence has attracted the attention of all students of Utah geology. Its position was noted by Howell (1875), and its regional relations and approximate dimensions were determined by Dutton (1880; 1882). Huntington and Goldthwait (1904), Gregory (1933), Dobbin (1939), Gardner (1941), and Thomas and Taylor (1941) have shown that the Hurricane fault, is not a single continuous fracture but rather a zone of fracturing and dislocation, generally narrow but in places as much as a mile wide; that movement along the fault has been intermittent; that the total displacement in various places ranges from less than 1000 feet to 8000 feet; that successive movements within the same general zone have broken all the Mesozoic and Tertiary formations in southwestern Utah; and that all the faulting is therefore post-Eocene (post-Wasatch), some of it doubtless Quaternary.

Of particular significance in geologic history is the demonstration that the Hurricane Cliffs record two major periods of faulting and an intervening period long enough for erosion to wear down the topographic inequalities produced by the first faulting before movement along the fault zone was renewed. In the Monument the features of the first faulting are obscure, the activity during the interfault cycle is recorded in stream patterns, and the effect of the second faulting is plainly revealed in the topography.

Where it breaks the strata along the west side of the Monument from Deadman Hollow to Spring Creek, the Hurricane fault is essentially a single fracture close to the base of the Hurricane Cliffs, in a few places accompanied by minor fractures with parallel or slightly divergent trends. Generally along this stretch of cliff the approximate position of the fault is shown in the topography, but the actual fault trace is concealed by alluvial fans and talus (Pl. 8, fig. 2). At Camp Creek, however, narrow zones of fractured rock and slickensides on the hard limestone and conglomerate seem to mark its course closely.

Within the Monument evidence for dating movements within the Hurricane fault zone is lacking. The youngest consolidated rocks exposed along the upthrown side of the fault—the Kaibab and Moenkopi formations—are Permian and Lower Triassic, and those on the downthrown side are concealed beneath alluvial fans, terrace gravels, and lava flows. Studies in neighboring regions, however, make it clear that the fractured rock, the discordant stratification, and the abrupt break in topographic profiles record only the latest disturbance within a zone of fracture. The faulting that produced the present Hurricane Cliffs is obviously very recent, and local earthquakes suggest that it may still be in progress. The escarpment on the upthrown (eastern) side remains in place as a nearly vertical wall immediately in contact with nearly flat surfaces on the downthrown (western) side; it nowhere has been reduced by erosion to a stable slope. Swift streams from the Kolob Terrace pass through the escarpment over waterfalls or through deep narrow gorges, but, on emerging from the cliff face, they abruptly assume very low gradients and wander across the flat lands westward. Displacement along the fault is measurable at Deadman Hollow, where sheets of larva have been broken. The basalt flows trenched by Ash Creek at the foot of the Hurricane Cliffs were doubtless once continuous with those on top of the cliffs at Pace Knoll and Black Ridge, which have been upfaulted about 1600 feet. A fault of such dimensions obviously has had a large part in determining the form of the Hurricane Cliffs and in guiding erosion in the Monument.

BEAR TRAP AND COUGAR MOUNTAIN FAULTS

Compared with the Hurricane fault, the Bear Trap fault and the Cougar Mountain fault are minor features. The Bear Trap fault, in the Navajo sandstone, has raised strata on the east about 500 feet. It has been chiefly effective in determining the position of valleys. The Cougar Mountain fault breaks the continuity of Triassic and Jurassic strata. In places it brings the basal Navajo sandstone into horizontal contact with the upper red sandstone of the Chinle formation. Its measured displacement is 480 feet.

THE KANARRA FOLD

In the Hurricane Cliffs, all along the western border of the Monument, the sedimentary beds are curved and tilted eastward in such a manner as to demonstrate the presence of a fold that in different places is a broad low arch, a steep-sided anticline, a compressed monocline, and a complex upwarp in which the beds are overturned (Pl. 1, insert). In the topography the structure is conspicuous; the edges of

its steeply dipping hard beds form parallel hogbacks (Pl. 8, fig. 1). For this feature, well displayed at Kanarraville, the term Kanarra fold has been selected.

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the Chinle; in Cave Valley, on the Navajo sandstone; and at Horse Ranch Mountain, on the Entrada sandstone. Evidence that latest volcanic activity followed the development of the present topography is the relation of lava flows to valleys. The outpouring lavas have utilized the valleys as ready-made runways, faithfully following their meandering courses. In places they have poured over cliffs. In Cave Valley, Lee Valley, and in large areas northeast of Pocket Mesa there was sufficient lava to obliterate the old drainage channels and to necessitate the establishment of new ones around and across the flows. Some streams of lava, especially along their lower stretches, only partly filled their chosen valley and thus allowed the pre-existing streams of water to maintain their general courses after minor readjustment.

In the absence of stratigraphic time markers more recent than the Entrada sandstone (Upper Jurassic), the age of the cones and flows can not be satisfactorily determined. The approximate date of regional volcanism, however, can be fixed with reference to faults and cycles of erosion, and the relative dates of eruption at various localities can be established by rough estimates of the amount and rapidity of erosion. Thus the lavas at Black Ridge at an altitude of 6500 feet appear to be parts of sheets that find their counterparts in Ash Creek Valley about 1600 feet below. The displacement was caused by the latest movements along the Hurricane fault, believed to have occurred in early Quaternary time. That the remnant lava flows along the crest of Hurricane Cliffs are relatively old is also shown by their form, position, and degree of weathering. Pace Knoll and Black Ridge are doubtless parts of once-continuous sheets of lava which have been largely stripped away. In contrast with these faulted and much-eroded remnants, most of the lavas in the Kolob volcanic field are remarkably fresh—even those that record intermittent eruptions. In form and structure some of the lava streams are so like those from volcanoes now active that it is difficult to think of them as more than a few centuries old. They retain their slaggy surface, roughened by broken blocks, and other irregularities produced by lateral pressure and by gas expansion. The cones, typified by Firepit Knoll, likewise seem youthful. Their outer slopes are normal for fragmental materials piled about volcanic vets, and their summit craters have characteristic form. Both inner and outer slopes are strewn with lapilli, bombs, and broken slabs of dense and scoriaceous basalt. Since they were formed, however, rain wash has gullied the slopes of cones and partly filled the craters, and streams have cut little canyons in the lava flows.

STRUCTURE

REGIONAL FEATURES

The Zion National Monument is the west-central edge of the great earth block between the Hurricane and Sevier faults and extends from the Colorado River northward to central Utah. East and south of the Monument the strata are horizontal or gently inclined except where interrupted by low folds and by faults of small dispalcement. Within the Monument all the strata have been much disturbed. The chief structural features are the prevailing high inclination of the strata, three

FIGURE 1. EASTWARD-DIPPING STRATA IN KANARRA FOLD BETWEEN LOCUST AND TAYLOR CREEKS
Shnabkaib and upper red members of the Moenkopi formation (Trm) (left); Shinarump conglomerate (Trs) (first ridge); Petrified Forest member (bench) and upper sandstones (base of cliffs) of the Chinle formation (Trc); Navajo sandstone (cliffs).

FIGURE 2. HURRICANE CLIFFS
Looking north across mouths of Wayne and Camp canyons. Escarpment of Kaibab formation (Ck), and Timpoweap member (Trmt) of Moenkopi formation represents upthrown block of Hurricane fault; alluvial fans thickly cover downthrown block.

STRUCTURAL FEATURES

faults (Hurricane, Bear Trap, and Cougar Mountain), and the Kanarra fold. The strata also exhibit low, broad folds, especially noticeable in the walls of canyons; sharply marked wrinkles, most of them monoclinal and involving several beds; and distortions confined to single beds. Prominent joints, singly and in groups, characterize the thick beds of sandstone and limestone, and many of them have been converted into faults with small throws—rarely more than a foot.

The sedimentary rocks dip northeastward (north, northeast, and east) (Pl. 1 (insert); Pl. 8, fig. 1); only the lavas are not conspicuously tilted. Along the Hurricane Cliffs the dips in most places measure 20°–80°, a few 90°. East of the Hurricane Cliffs the dips decrease, in some places abruptly, in others gradually, until in the upper La Verkin canyons dips of more than 2° are exceptional. South of Jobs Head and Firepit Knoll, dips of 2°, 1½°, 1°, and ½° are representative.

HURRICANE FAULT

Next to the prevailing tilt of the strata the outstanding feature of the regional structure is the Hurricane fault—a master belt of displacement in the plateau country of Utah and Arizona. Throughout its length of approximately 200 miles, from the Aubrey Cliffs south of the Colorado River to the base of the Tushar Mountains in west-central Utah, movements along the Hurricane fault have profoundly disturbed the sedimentary and igneous rocks and remodeled the topography by bringing high plateaus in abrupt contact with broad expanses of lowland. In Utah, this great zone of dislocation marks the position of the lofty Hurricane Cliffs which divide the belt of farms and orchards about Hurricane, La Verkin, Toquerville, Midway, Kanarraville, Fort Hamilton, Cedar City, Summit, Parowan, and Paragonah from the uninhabited, high-lying grazing lands of the Little Creek Terrace, Kolob Terrace, and the Markagunt Plateau. Naturally, a feature of such geologic and geographic prominence has attracted the attention of all students of Utah geology. Its position was noted by Howell (1875), and its regional relations and approximate dimensions were determined by Dutton (1880; 1882). Huntington and Goldthwait (1904), Gregory (1933), Dobbin (1939), Gardner (1941), and Thomas and Taylor (1941) have shown that the Hurricane fault, is not a single continuous fracture but rather a zone of fracturing and dislocation, generally narrow but in places as much as a mile wide; that movement along the fault has been intermittent; that the total displacement in various places ranges from less than 1000 feet to 8000 feet; that successive movements within the same general zone have broken all the Mesozoic and Tertiary formations in southwestern Utah; and that all the faulting is therefore post-Eocene (post-Wasatch), some of it doubtless Quaternary.

Of particular significance in geologic history is the demonstration that the Hurricane Cliffs record two major periods of faulting and an intervening period long enough for erosion to wear down the topographic inequalities produced by the first faulting before movement along the fault zone was renewed. In the Monument the features of the first faulting are obscure, the activity during the interfault cycle is recorded in stream patterns, and the effect of the second faulting is plainly revealed in the topography.

Where it breaks the strata along the west side of the Monument from Deadman Hollow to Spring Creek, the Hurricane fault is essentially a single fracture close to the base of the Hurricane Cliffs, in a few places accompanied by minor fractures with parallel or slightly divergent trends. Generally along this stretch of cliff the approximate position of the fault is shown in the topography, but the actual fault trace is concealed by alluvial fans and talus (Pl. 8, fig. 2). At Camp Creek, however, narrow zones of fractured rock and slickensides on the hard limestone and conglomerate seem to mark its course closely.

Within the Monument evidence for dating movements within the Hurricane fault zone is lacking. The youngest consolidated rocks exposed along the upthrown side of the fault—the Kaibab and Moenkopi formations—are Permian and Lower Triassic, and those on the downthrown side are concealed beneath alluvial fans, terrace gravels, and lava flows. Studies in neighboring regions, however, make it clear that the fractured rock, the discordant stratification, and the abrupt break in topographic profiles record only the latest disturbance within a zone of fracture. The faulting that produced the present Hurricane Cliffs is obviously very recent, and local earthquakes suggest that it may still be in progress. The escarpment on the upthrown (eastern) side remains in place as a nearly vertical wall immediately in contact with nearly flat surfaces on the downthrown (western) side; it nowhere has been reduced by erosion to a stable slope. Swift streams from the Kolob Terrace pass through the escarpment over waterfalls or through deep narrow gorges, but, on emerging from the cliff face, they abruptly assume very low gradients and wander across the flat lands westward. Displacement along the fault is measurable at Deadman Hollow, where sheets of larva have been broken. The basalt flows trenched by Ash Creek at the foot of the Hurricane Cliffs were doubtless once continuous with those on top of the cliffs at Pace Knoll and Black Ridge, which have been upfaulted about 1600 feet. A fault of such dimensions obviously has had a large part in determining the form of the Hurricane Cliffs and in guiding erosion in the Monument.

BEAR TRAP AND COUGAR MOUNTAIN FAULTS

Compared with the Hurricane fault, the Bear Trap fault and the Cougar Mountain fault are minor features. The Bear Trap fault, in the Navajo sandstone, has raised strata on the east about 500 feet. It has been chiefly effective in determining the position of valleys. The Cougar Mountain fault breaks the continuity of Triassic and Jurassic strata. In places it brings the basal Navajo sandstone into horizontal contact with the upper red sandstone of the Chinle formation. Its measured displacement is 480 feet.

THE KANARRA FOLD

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OUTLINE OF GEOLOGIC HISTORY

PALEOZOIC AND MESOZOIC

The geologic history of Zion National Monument is revealed by the sedimentary and volcanic rocks, faults and folds, fossils, and topography. The consolidated sedimentary rocks record the events of Mesozoic and very late Paleozoic times; the lavas, the deposits of alluvium, and the topography of the present surface record events of Quaternary and Recent times.

An outstanding feature of the consolidated sediments is their relative freedom from disturbance by local earth movements. Though the presence of beds formed in the sea, in shoreline lagoons, on coastal planes, and inland areas testifies to regional changes of altitude with respect to sea level, the evidence seems clear that most of the Mesozoic formations were deposited on surfaces of very slight relief and remained substantially parallel and horizontal during sinkings and elevations and long intervening periods of quiescence. In the Monument, as in adjoining regions, the oldest tectonic feature is the post-Mesozoic Kanarra fold, and the next oldest is the Tertiary and Quaternary Hurricane fault.

The basal formation in the Monument is the Permian Kaibab—a representative part of widely spread strata of marine limestone. After deposition the Kaibab rose above the sea and for a long time was exposed to erosion; the topmost beds are gullied and beveled off and in places removed. Generally on the rough surface of the Kaibab a coarse conglomerate, largely of exotic pebbles, was laid down by streams, then gradually depressed beneath the sea. This conglomerate and the marine limestone and shale above it constitute the Timpoweap member of the Moenkopi formation of Lower Triassic age—the lowest major unit in the Triassic of southwestern Utah. Above the Timpoweap, the Moenkopi includes three series of beds (lower, middle, and upper red beds) deposited on land, one group of beds formed in open sea water (Virgin limestone member), and one probably laid down in restricted waters near shore (Shnabkaib gypsiferous member). Except for an unconformity at the base of the Virgin limestone member clear evidence of pauses in deposition are lacking; one class of beds merges imperceptibly into another. Thus, seemingly, the intermittent changes from sinking to rising of the land were slow and uninterrupted. The close of Moenkopi (Lower Triassic) time was marked by widespread and profound erosion. A landscape of shallow streamways and low divides was developed—a plain-like surface that extended over thousands of square miles. On this surface of erosion were deposited the sands and gravels and the logs and fragments of wood that make up the remarkable Shinarump conglomerate—a formation defined as the base of the Upper Triassic.

With no apparent break, the Shinarump is overlain by the brightly colored sandstones and shales of the Chinle formation. The entire Chinle was deposited on land, along streams, and in bodies of standing water; the fossils in it are wood, land shells, dinosaur bones, and fresh-water fish. In restoring the geography of Chinle time it is reasonable to visualize shallow broad streams descending gentle slopes and winding through lowlands—streams with many sand bars and bordered in places by swamps and lagoons. Though the streams probably could not cut deeply or carry large

quantities of coarse rock waste, they could transport unlimited amounts of sand and sweep from the surface and grind up trees and skeletons of animals. Continuity of stream action is shown in the mass of thin-bedded lenticular sandstone which totals more than a 1000 feet in thickness. The presence of shallow-water bodies is shown by thin-bedded shales, limestone, and silts—especially in the Petrified Forest member, so named because of its "forests" of fossil wood. In the upper part of the Chinle formation lacustrine deposits are very rare. The humid climate of early Chinle time became more arid toward the close of the period, and without recognizable interruption the topmost strata of the Chinle, which mark the end (?) of Triassic time, grade into the Navajo sandstone, which is the basal Jurassic in Zion National Monument. The Navajo is essentially an undivided mass of sandstone more than 1500 feet thick and is the outstanding cliff maker of the region. Its composition and texture, its marvelous cross-bedding, and its extremely small content of fossils indicates general aridity; in fact, large parts of it seem little more than consolidated sand dunes.

At the close of Navajo time the sea spread over the desert lands and remained long enough to deposit the limey silts that make up the Carmel formation and the gypsiferous sands of the Entrada sandstone, both of Upper Jurassic age. In the Monument the strata younger than the Entrada have been removed by erosion, but they are displayed near by, and there is little doubt that all the Upper Jurassic, as well as the Cretaceous and the Tertiary formations, once covered the entire region.

QUATERNARY AND RECENT

Quaternary and Recent times are recorded in uplifts, erosion, and lava flows. In a broad sense it is the history of post-Eocene stream work—in large part probably post-Miocene—controlled by altitude and conditioned by climate and tectonic movements. The present topography measures the progress of adjustment of drainage to structure.

Before they were raised to their present position in late Tertiary and Quaternary times the rocks in the Monument are believed to have stood not far above sea level. The topography doubtless was characterized by flat surfaces, broad, shallow valleys, and scattered volcanic cones—something like the present landscape along the road east of Cedar Breaks National Monument. The conversion of these simple topographic features into the present heterogeneous assemblage of canyons, mesas, fault cliffs, valley walls, terraces, plateau remanants, and generally discordant profiles has been a gigantic task, obviously not performed at one time nor under uniform conditions. During the profound remodeling of the landscape there were periods when streams vigorously cut into rock, periods when they were filling their channels with sand and gravel, periods of uplift and of stillstands, and periods of humid and arid climate.

Disregarding the shorter periods of erosion and the smaller fault movements, it is practicable to outline two major cycles of erosion, each initiated by regional uplifts. The older cycle—the pre-canyon cycle—began with a post-Miocene uplift which raised widespread low-lying rocks nearly to the height of the present Markagunt Plateau. As measured by the displacement of strata along the Hurricane fault, the

amount of uplift exceeded 5000 feet. During this cycle the Tertiary and Cretaceous and some of the flat-lying Jurassic sedimentary rocks were stripped away from the Monument down to the Carmel limestone, which forms the generally flat lands north of Jobs Head and east of Horse Ranch Mountain. Streams also beveled the edges of steeply tilted strata, producing such roughly level surfaces as that preserved beneath the lavas at Black Ridge. The second cycle—the canyon cycle—began with an uplift recorded in the Hurricane fault as more than 800 feet. As the result of this uplift the streams, slow moving and meandering at the close of the pre-canyon cycle, were given very steep gradients and consequently great power to erode. The streams entrenched themselves deeply with little regard to kind and attitude of the rocks encountered. The canyon cycle is the present major cycle of erosion. So far, streams have cut deep narrow trenches into the eroded surface made during the pre-canyon cycle; they have made of Zion National Monument a land of canyons and cliffs (Pl. 9). Other events within the canyon cycle are the outpouring of lava from cones and concealed vents; a recent change from stream cutting to stream deposition that has partly filled the canyons with rock waste; and the excavation within historic times of much of this waste to form the terraces that line many channels.

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GENERALIZED VIEW OF T
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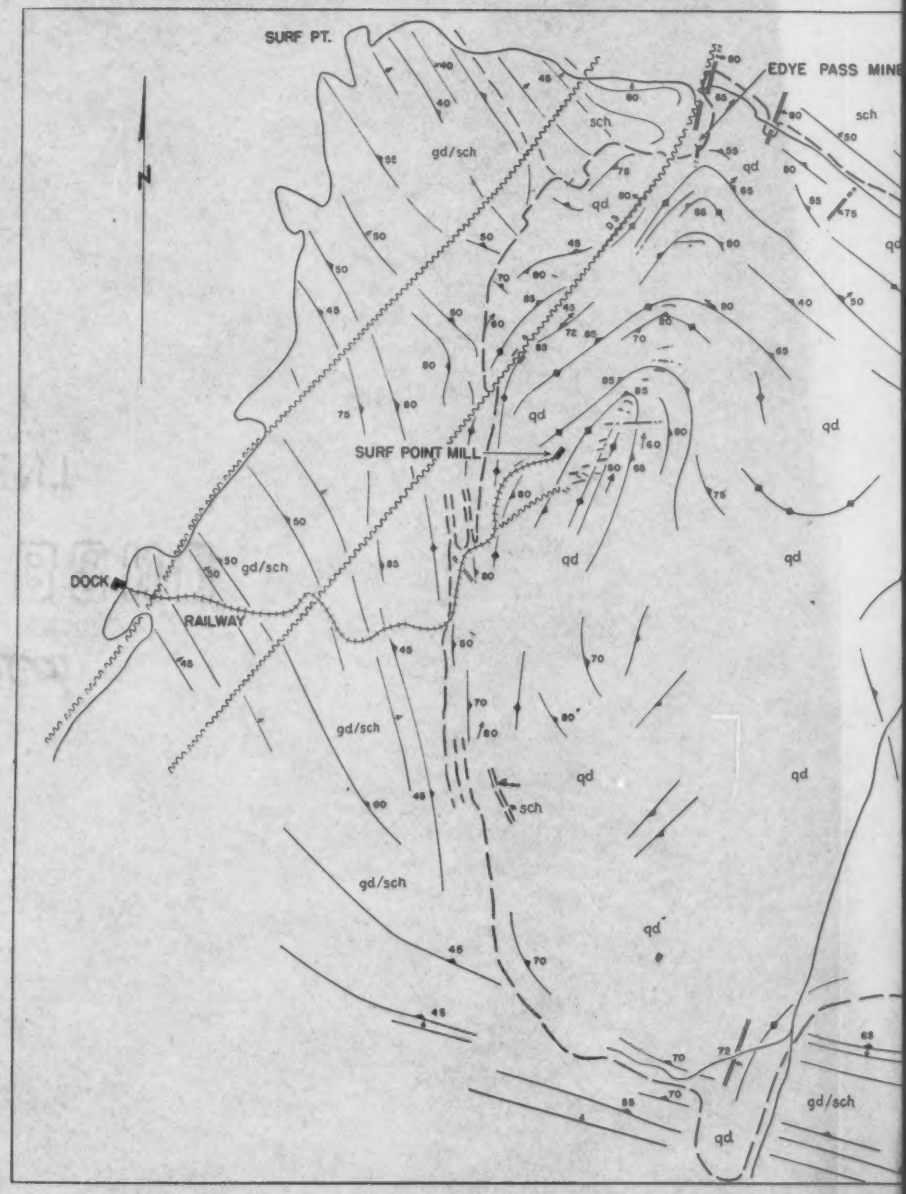
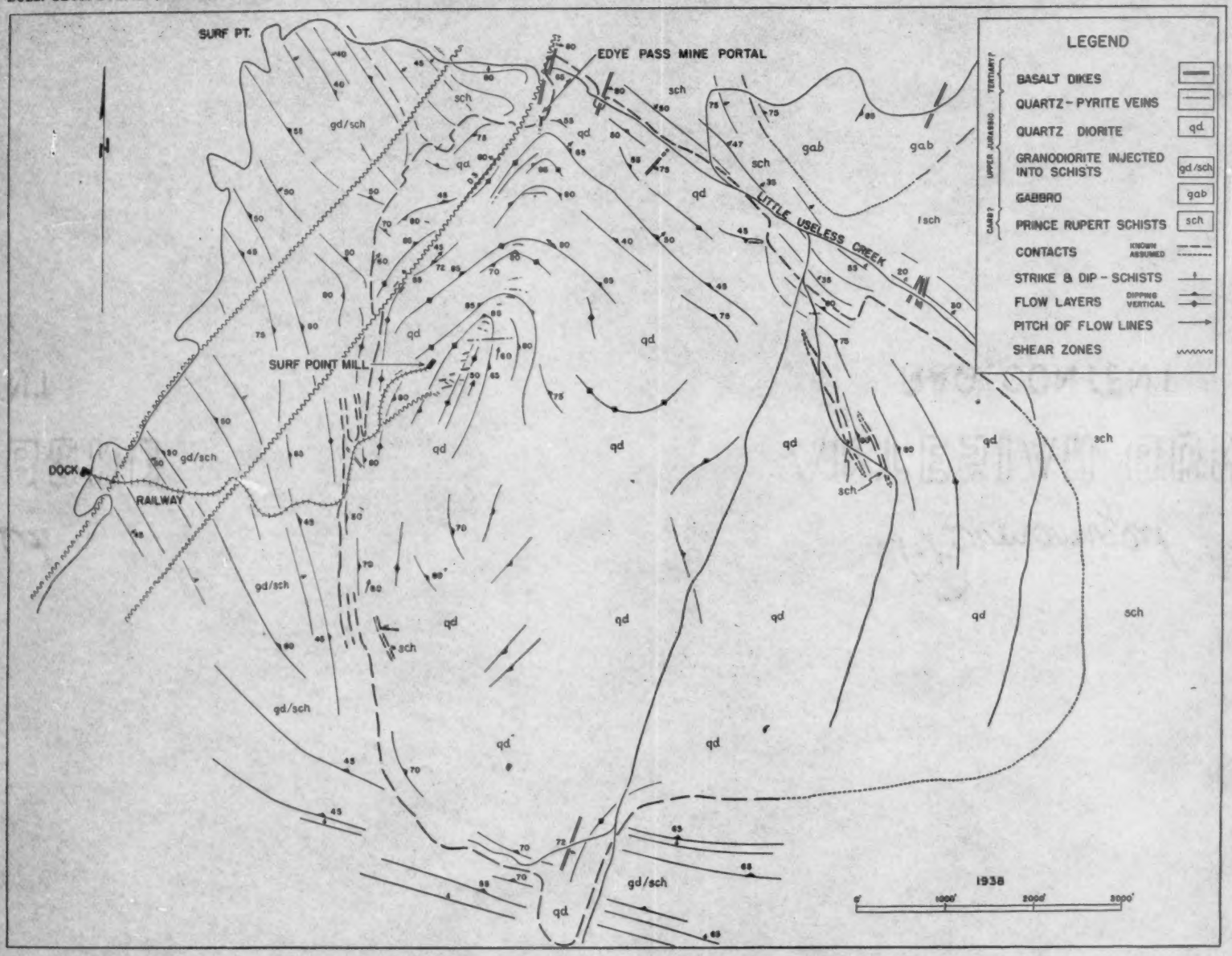
VIEW OF THE REGION THAT INCLUDES ZION NATIONAL MONUMENT
Looking north from highlands along the Virgin River



GEOLOGIC MAP, NORTHWEST PORTION



GEOLOGIC MAP, NORTHWEST PORTION PORCHER ISLAND

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CONTROL OF ORE BY PRIMARY IGNEOUS STRUCTURES, PORCHER ISLAND, BRITISH COLUMBIA

BY ALEXANDER SMITH

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ABSTRACT

The ore deposits at Surf Point and Edye Pass Mines, Porcher Island, British Columbia, lie in a quartz diorite stock. They are a series of auriferous quartz-pyrite veins occurring in a N. 20°E. zone along the axis of an arch of flow layers. Strong N. 30°E. shears in an adjacent to the stock aided in the enlargement of the magma chamber. The same stresses acting in the arch formed the ore-bearing structures by a series of small transverse movements involving the primary joints. Study of the internal structures gave valuable information on the form of the stock and the extension of the ore-bearing zone.

INTRODUCTION

GENERAL STATEMENT

Mapping internal structures of an intrusive has proven of value in quarrying. Only about a dozen examples appear in the literature of metalliferous deposits in intrusives occupying primary features; these are veins in cross joints or marginal upthrusts (Emmons and Grout, 1935; Kerr, 1936; Barr and Gardner, 1940). The lode deposits described in this paper show structural control by a primary flow structure, an arch of flow layers.

The area studied is the northwest portion of Porcher Island, B. C. (Fig. 1). The principal deposits are those of the Surf Point and Edye Pass mines. These properties lie about 25 miles southwest of Prince Rupert, B. C., the western terminus of the north branch of the Canadian National Railways.

The climate is wet and equable. Temperatures remain below freezing for only a few weeks each year. Most of region is heavily forested with spruce, hemlock, and red cedar, but adjacent to the mines muskeg, moss, and scrub cover most of the area mapped. Although bedrock commonly lies near the surface, outcrops, excepting along the shore line, in the mine workings, and at higher elevations, are isolated and small. However, as a result of Pleistocene glaciation, they are of fresh rock. The relief in the area mapped varies from sea level to a maximum of 2200 feet on the ridge south of Surf Point Mine.

PREVIOUS WORK IN AREA

The geology of the coast line and islands of the northerly portion of British Columbia has been mapped and described by Dolmage (1922). The progress of the

properties has been reported on by Mandy (1928–1935). Legg (1934) described the milling methods at Surf Point, and Warren and Cummings (1936) investigated the ores microscopically.

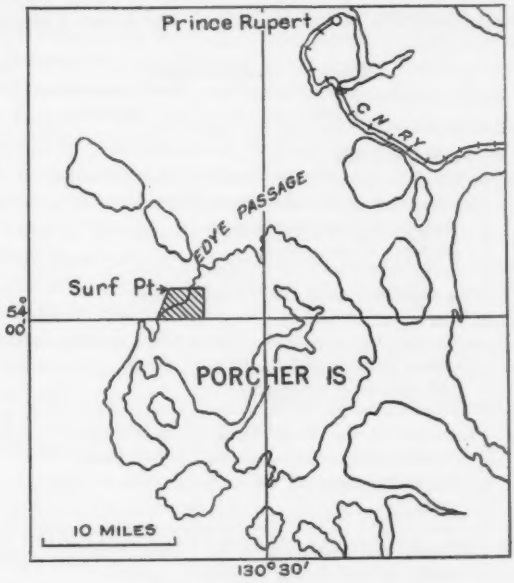

FIGURE 1.—*Key map to area*

PURPOSE AND EXTENT OF THE PRESENT STUDY

The primary purpose of this investigation was to determine the structural control of ore bodies in a quartz diorite stock, thereby furnishing a geological guide in the development of the deposits. The principles and technique employed were those developed by Hans Cloos and his coworkers and admirably described by Balk (1937).

Structures were mapped in great detail. Plates 1 and 2 are generalized from field maps, of scales 1 inch equals 300 feet and 1 inch equals 100 feet, respectively, on which hundreds of flow and fracture orientations were recorded. Mapping included adjoining areas and adjacent islands. Since this work did not add materially to the interpretation of the igneous structures, however, it has been omitted from the present report.

ACKNOWLEDGMENTS

The writer is indebted to Dr. V. Dolmage for suggesting application of the Cloos methods to the problem of control of the ore deposits. The field work was completed in the summer of 1938. The writer wishes to express his sincere thanks to Dr. Ian Campbell of the California Institute of Technology, under whose guidance and supervision the study has been completed.

GENERAL GEOLOGY

RELATIONSHIP OF THE AREA TO THE COAST RANGE BATHOLITH

The quartz diorite stock in which the ore deposits occur is a satellite of the composite Coast Range batholith of Upper Jurassic and Lower Cretaceous age (Bud-

TABLE 1.—*Geologic column*

Age	History	Formation	Lithology
RECENT	Postglacial uplift.		
PRE-PLEISTOCENE	Long period of erosion with repeated uplift and peneplanation. Intrusion of small dikes.	Dikes.	Andesites, basalts.
UPPER JURASSIC	Ore deposition in quartz diorite stock.	Veins.	Auriferous quartz-pyrite veins.
	Faulting along N. 30° E. shears and associated movements.		
UPPER JURASSIC	Intrusion of the Coast Range batholith and the associated minor intrusives of the map area.	Coast Range intrusives.	Quartz diorite, granodiorite, gabbro.
UPPER JURASSIC	Dynamic metamorphism of the rocks of the Prince Rupert series.	Prince Rupert schists.	Amphibolite schist.
CARBONIFEROUS AND/OR TRIASSIC	Vulcanism and sedimentation.	Prince Rupert series.	Andesites, basalts.

dington and Chapin, 1929, p. 252–253). The western contact of the main batholith lies about 20 miles to the east. West of the massive batholithic rocks there is, along the coast and islands, a wide zone in which older rocks are injected by smaller bodies of Coast Range intrusives. Porcher Island lies in this western marginal zone. Much the greater part of the island consists of older rocks, but there are numerous small, and a few larger, bodies of the intrusives (Dolmage, 1922).

GEOLOGIC HISTORY

General statement.—The significant events of the geologic history of the map area are summarized in Table 1.

Prince Rupert schists.—The Prince Rupert schists are highly metamorphosed rocks, contain varying amounts of amphibole, pyroxene, chlorite, mica, and garnet with a few layers of limestone included (Dolmage, 1922), and are Carboniferous and/or Triassic in age. In this area the series are principally amphibolite schists derived by dynamic metamorphism of andesitic and basaltic flows, tuffs, and sills. The

schists attained their present characteristics prior to the injection of the small Coast Range intrusives of the map area. Their metamorphism, however, is associated with the intrusion of the batholith (Buddington and Chapin, 1929, p. 293–298).

The regional strike of the schistosity is NW. with an average dip of 50°NE. Bedding, in the few cases where it could be determined, parallels the schistosity.

Coast Range intrusives.—In addition to the quartz diorite stock, one small mass of gabbro and numerous sill-like injections of granodiorite occur. The gabbro lies east of Little Useless Creek as a small isolated body in the schists.

The quartz diorite (tonalite) stock in which the veins occur is about $1\frac{3}{4}$ miles in diameter. It is subcircular in outline; the contact is fairly regular without large protuberances or re-entrants. The intrusive is rather uniform in composition and texture, but toward the core the rock becomes more leucocratic and approaches a granodiorite in appearance and composition. This gradation between quartz diorite and granodiorite is common in the Coast Range batholith (Dolmage, 1922, p. 15). Small gray inclusions, characteristic of the normal quartz diorite, become scarcer toward the central portion and are not present in the granodiorite core. There is no well-defined basic border facies in the intrusive nor any noticeable zone of thermal metamorphism in the country rock. Although the actual contact with the schists is rarely exposed, it appears to be fairly sharp.

Sill-like bodies of granodiorite, ranging in thickness from a few inches to several hundred feet, intrude the schists, often in *lit-par-lit* relationships. In the map area the volume of granodiorite injected into the schists exceeds the volume of the schists. In the field this granodiorite can readily be distinguished from the normal quartz diorite by its more leucocratic appearance and the abundance of small barren quartz veinlets. Megascopically it is similar to the granodiorite core of the satellite.

The age and structural relationships of the granodiorite injections with respect to the quartz diorite are not clear. Although the areal distribution of the granodiorite is widespread and is not related to the quartz diorite satellite, yet in the map area their relationship might suggest that the granodiorite was a *lit-par-lit* injection of an acid phase of the quartz diorite magma into the schists. There is no evidence that the granodiorite sills postdate the stock. Most of the injections probably preceded intrusion of the stock, but the structural relations along the western margin of the stock suggest that some may have been injected during the intrusion of the stock as offshoots from the quartz diorite magma.

Ore deposits.—Following the intrusion of the quartz diorite, faulting occurred in, and adjacent to, the stock along shears trending N. 30° E. At the same time movement along pre-existing joint planes formed the future ore-bearing structures.

The ore deposits are auriferous quartz-pyrite veins with the values enclosed in the pyrite as minute blebs of telluride and free gold (Warren, 1936). They are of a rather high-temperature, close to hypothermal, origin. Individual quartz veins vary in width from a fraction of an inch up to 2 or 3 feet. The average assay of such vein material is of the order of 1 ounce gold per ton. The pure pyrite assays about 8 ounces gold per ton. A few small veins occur in the schists near the contact, but most of the veins lie within the quartz diorite in a zone trending N. 20° E. They vary in strike from N. 30° E. to S. 80° E. and dip from 60° N. to vertical.

Post-ore history.—Basalt and andesite dikes cut the schists, the quartz diorite, and the ore. They are the only post-ore formations in the area. These dikes may be much younger than the ore deposits. Basalt and andesite flows and dikes of Tertiary and Quaternary age are found in near-by areas on the coast (Dolmage, 1922).

The Tertiary history of the region is one mainly of repeated uplift and erosion. Pleistocene glaciation stripped the map area of all weathered rock, soil, and detritus.

PRIMARY FLOW STRUCTURES

INTRODUCTORY STATEMENT

Except in the core of the stock, faint flow layers are discernible. There is a good platy alignment of small inclusions and hornblende crystals. However, there are no well-defined schlieren, basic clots, or segregations into light and dark bands. The inclusions are pancake-shaped or ellipsoidal; the hornblende crystals are tabular or prismatic. The largest faces of the inclusions and of the hornblende tend to lie in parallel planes. Flow lines, resulting from the alignment of elongated inclusions or hornblende, have an almost constant trend. They often lie in the plane of the flow layers, but the trend of some flow lines transects the plane of the flow layers.

FLOW LAYERS

Near the margins of the stock, flow layers invariably parallel the nearest contact. On the northeast and southwest margins of the intrusive, the contact and the flow layers parallel the trend of the intruded schists. Along the western contact, in the northerly section, flow layers and contact strike northeast at a high angle to the trend of the schists. Toward the south the internal structures of schists and intrusive again become concordant.

The most striking structural feature in the intrusive is a well-defined arch of flow layers (Pls. 1, 2). The axial plane of this arch strikes N. 20° E. and dips about 85° SE. subparallel to the trend of strong N. 30° E. shears. The northerly plunge of the arch increases from 55° at the north contact to over 85° near the core. The flow layers in this arch are arranged in a nose comparable to a steeply plunging anticline in sedimentary rocks.

Southward along the axis of the arch the flow layers become fainter until in the southern portion of Surf Point Mine workings (Pl. 2) they cannot be distinguished along the axis although they are still strongly developed on the flanks. Here the layers nearly parallel the axial plane of the arch—*i.e.*, the structure is tighter and isoclinal. There is a local divergence between the platy alignment of inclusions and of hornblende (Fig. 2) with the inclusions forming a more open arch. In this core zone the quartz diorite grades into granodiorite.

The arch of flow layers probably continues south of Surf Point Mine. As the flow layers along the southern margin of the intrusive dip 65° N., these layers, combined with the arch of flow layers, may form an elliptical funnellike structure, pitching northeast and tapering upwards (Fig. 9). Other less well-defined arches occur. No detailed field work was done on the southeastern portion of the stock, hence on

the map (Pl. 1) the lack of detail does not mean that the intrusive in this section is devoid of flow structures.

FLOW LINES

Linear structures in the quartz diorite are neither so widespread nor so easily identified as the flow layers, but their trend is more regular.

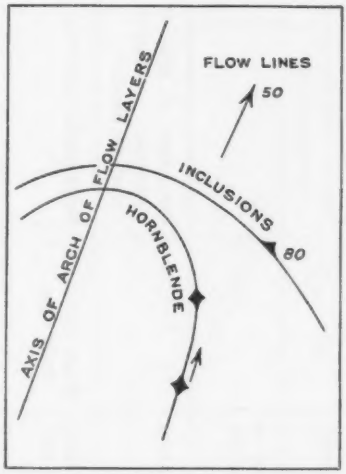

FIGURE 2.—*Divergence of flow structures*

Along the northeast margin the flow lines subparallel the dip of the overlying schists—*i.e.*, pitch 55° NE.

On the arch of flow layers, the lineation trends almost parallel to the axis but has a more gentle and constant pitch of about 55° NE. On the flanks, flow lines dipping about 50° NE. occur within the plane of the flow layers. Locally a lineation with this trend is found where flow layers are not discernible. Exceptions to the relatively constant trend of the lineation occur on the axis of the arch where flow layers dip steeply (80°). Here flow lines are uncommon, but occasionally a lineation of variable pitch, sometimes horizontal, is found in the plane of the flow layers.

If one were to disregard the platy structures and plot only the flow lines the stock would show a regular pattern of linear structures striking N. 20°–30° E. and dipping about 50° NE. No arch or nose would be apparent. The general trend of the lineation is slightly more easterly than the N. 20° E. axis of arch of flow layers (Fig. 4).

JOINT PATTERN

GENERAL STATEMENT

The joint systems in the quartz diorite are more closely related in orientation to linear structures in the intrusive and to regional jointing in the schists than to the

TABLE 2.—*Joint sets*

Set	Orientation		Rock	Characteristics		Relation to flow structures or schistosity	System
	Strike	*Dip*		*Persistency, Spacing*	*Filling*		
1	N.20°–30° E.	65°–85° SE.	Schist	Continue into intrusive, nearly parallel to N.30 E. shears.	Basalt dikes.	Nearly normal to schistosity.	Tension joints.*
			Intrusive	Continue into schists.	Basalt dikes.	Parallel to trend of flow lines and axial plane of arch of flow layers.	Primary longitudinal joints?*
2	N.40° W.	50° NE.	Schist	Common, persistent, parallel to schistosity.		Plane of schistosity (plane of maximum shear).	Plane of schistosity.
			Intrusive	Common only south of mines. Spacing 5–30 feet, persistent.			?
3	N.40° W.	50° SW.	Schist	Common persistent spacing 1–5 feet.		Complement of plane of schistosity. Plane of maximum shear.	
			Intrusive	Even, remarkably persistent, spacing 10–50 feet, slickensides.	Gouge pyrite, andesite dikes.	Nearly normal to flow lines.	Primary cross joints?*
4	N.75° W.	65°–85° NE.	Schist	Not persistent.		Diagonal to schistosity.	Diagonal joints?
			Intrusive	In zones of closely spaced joints along arch of flow layers, some slickensides.	Quartz-pyrite veins.	Diagonal to flow lines. Planes of shear.	Primary diagonal joints?*
5	N.65° E.	55°–85° NE.	Schist	Not persistent.		Diagonal to schistosity.	Diagonal joints?
			Intrusive	In zones of closely spaced joints along arch of flow layers, some slickensides.	Quartz-pyrite veins.	Diagonal to flow lines. Planes of shear.	Primary diagonal joints?*

arch of flow layers. The attitude of the flow layers, however, influences the frequency and persistency of joints of a given orientation. Several prominent joint sets occur in both schist and intrusive, but the age and genetic significance of these joints may differ in the two rocks. Certain types in the intrusive have been classed as primary joints, but this designation is not nearly so clear cut as in the case of some larger intrusives (Balk, 1937, p. 97–117).

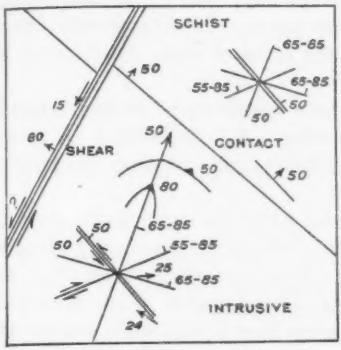

FIG. 3

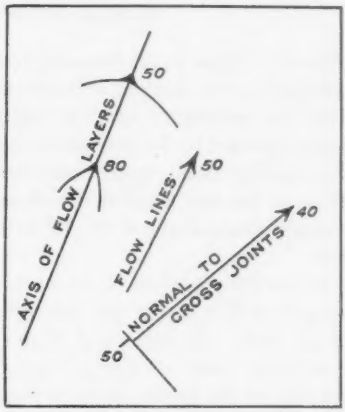

FIG. 4

FIGURE 3.—*Relationship of flow and joint patterns*
FIGURE 4.—*Progressive eastward rotation of succeeding primary structures*

JOINT SYSTEMS

Table 2 summarizes the information regarding the principal joint sets in schist and intrusive and their relationships to flow structures and schistosity. (*See also* Figure 3.) These types may vary 10°–15° in strike or dip from the orientation given. In the schists this variation seems systematic and seems to correspond to a change in the trend of the schists. Locally other sets of joints occur, but they are less numerous and constant than the types described.

The age relationships and genetic significance of the various types in schist and intrusive are not fully understood. In the schists many of the joints may antedate the intrusion. Types common to both intrusive and schist may be either related to the intrusion or of postintrusive age. Even some of the primary joints in the intrusive could be expected to have the same orientation as older joints in the schists, for joints (Table 2, types 1 and 2) in the schists played an important part in the emplacement of the quartz diorite. Flow lines, which control the orientation of primary joints in the intrusive, parallel the dip of the schists.

PRIMARY JOINTS IN THE INTRUSIVE

Joints of types 1, 3, 4, and 5 in the intrusive might, on the basis of their orientation relative to the lineation, be classed as primary joints (Balk, 1937, p. 27–42). They

would be longitudinal joints (type 1); cross joints (type 2); and diagonal joints (types 4, 5). Their persistency, spacing, surface characteristics, and fillings correspond closely to descriptions in the literature. However, some doubt is cast on their primary origin by the occurrence in the schists of joints of similar orientation and by anomalous features such as an unusual orientation of slickensides on diagonal joints.

INFLUENCE OF FLOW LAYERS ON JOINTING

On the arch of flow layers the orientation of the primary joint system is apparently little affected by the changing attitude of the flow layers. Yet, in any portion of the structure, the continuity, spacing, and even the types of joints which occur, are seemingly governed by the attitude of the layers.

This control probably results from the structural anisotropy of the quartz diorite. The plane of the flow layers is one of easy splitting. It is difficult for the rock to split along planes at angles of 20°–70° to the flow layers except on planes including the lineation.

In the northerly portion of the arch, diagonal joints are conspicuous where the orientations of flow layers and joints coincide. This occurs principally along the axis of the arch. At Surf Point Mine in the central area of the stock where flow layers are faint, zones of closely spaced diagonal joints (types 4, 5) are strongly developed; but on the flanks, where strong flow layers lie at a high angle to these joint directions, these zones of close jointing die out. Even the cross joints (type 3) seem to be more frequent and persistent in the central area.

This control of jointing by flow layers has in turn influenced the ore-bearing structures as will be discussed in a later section.

MODE OF EMPLACEMENT OF THE QUARTZ DIORITE

THEORY OF INTRUSION DEVELOPED BY H. CLOOS

Before discussing the mechanics of emplacement of the quartz diorite it will be desirable to summarize the theories developed by H. Cloos (1925). The following paragraphs are abstracted from Balk's discussion (1937, p. 78–83).

During the early stages of intrusion it is believed that a highly mobile magma or crystal mush ntrudes a relatively rigid and mechanically resistant crust. Such a mass must encounter a maximum of retardation of motion along its contact planes. Segregations, inclusions, and tabular crystals will be drawn out into flow layers (schlieren) which thus develop approximately parallel to the nearest contact.

As more and more magma intrudes, the mechanical resistance of the crust is weakened, and the roof or flanks of the chamber begin to yield by folding or faulting. In this second stage the adjacent crust partakes in the motion of the igneous core. There is no longer along the contact the extreme friction and retardation of the magma which in the earlier stages formed the schlieren. Linear flow structures which disregard local contact planes form in the direction of maximum linear expansion. For hundreds of square miles the projected strike of flow lines lie within flow layers, the individual grains had enough freedom to move slightly within the plane of the layers. A few cases are known where isolated flow layers dip more steeply than does the pitch of the flow lines between the layers. Mineral grains within flow layers rich in ferromagnesian crystals may not have been free to rotate any longer, but crystals in the more mobile surrounding magma may have been arranged in accordance with the feeble linear elongation of the magma. The older an arch of flow layers, the longer it will have participated in the subsequent arching, thus attaining steeper dip angles.

APPLICATION OF THEORY TO STRUCTURES IN QUARTZ DIORITE STOCK

General statement.—The flow structures in the quartz diorite conform closely to the theory outlined above. The parallelism of the layers to the nearest contact is very noticeable. The constant pitch of the lineation to the northeast indicates that, during the second stage of explacement, the direction of maximum elongation of the

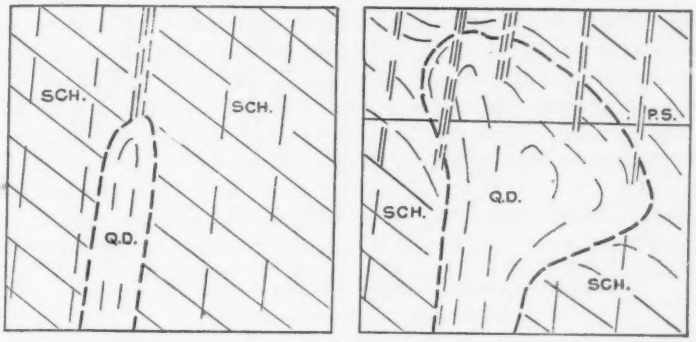

FIGURE 5.—*Early intrusion along shear and later mushrooming*
Looking north. P. S. = present surface level.

quartz diorite magma for the levels exposed was upward to the southwest, *i.e.*, up the dip of the schists.

Origin of the arch of flow layers.—The origin of the well-developed arch of flow layers might be explained in several ways. Among the possibilities are:—

(1) Prior to intrusion a steeply dipping, northeast-trending shear (or joints of type 1 with similar trend) was present in the area now occupied by the arch of flow layers (Fig. 5). The earliest magma rose nearly vertically in this shear, gradually prying it open to the northward and developing the steep arch of flow layers in almost its present form. In the second stage the magma enlarged its chamber by mushrooming out mainly to the northeast of the shear and by doming its cover. The linear structures indicate that the greatest elongation of the igneous body during this later stage paralleled the dip of the schists.

(2) The magma rose from the northeast paralleling the schistosity (Fig. 6). Flow layers were developed, dipping northeast parallel to the contact. The magma chamber increased in size by faulting along the northeast-trending shears. In this explanation the shears need not have been preintrusive. If they resulted from intrusion they could have followed planes of weakness provided by joints of type 1 in the schists.

The offset of the cover along the shear folded the flow layers into the steeply plunging arch. The occasional almost horizontal lineation found in the steeply dipping flow layers on the axis may have formed during this folding.

(3) The walls of the magma paralleled the schistosity on the northeast contact, and the N. 30° E. joints (type 1) on the northwest contact (Fig. 7). Over the area

of the arch of flow layers magma rose, along a shear or zone of weakness, above the general level of the roof. This upsurge of magma to higher levels formed the arch of flow layers.

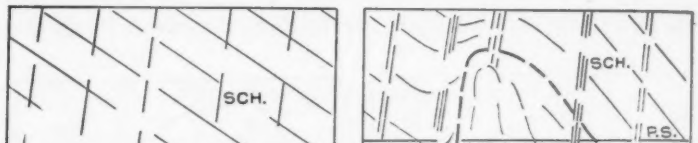

FIGURE 6.—*Intrusion paralleling schistosity and later offset of cover*
Looking north. P. S. = present surface level.

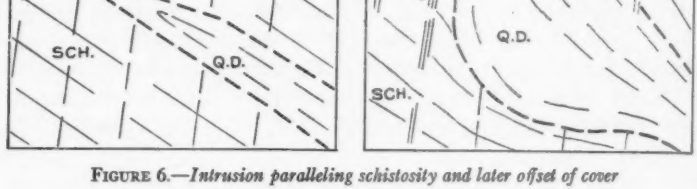

FIGURE 7.—*Late upsurge along shear*
Looking north. P. S. = present surface level.

There is no conclusive field evidence to indicate which, if any, of these alternatives is the mode of origin of the stock. The writer regards (1) and (2) as being equally probable. There is no proof, in (1), of a preintrusive shear or of mushrooming of the chamber, or, in (2) of actual folding of the flow layers. Case (3) offers an explanation only for the steep arch of flow layers and does not apply to the intrusion of the entire stock.

Whatever the origin of the arch of flow layers, it is evident that structures in the schists, the plane of schistosity, and the N. 30° E. shears or joints exerted a marked control during the emplacement of the intrusive and the development of the arch.

Evidence of forceful intrusion.—Enlargement of the magma chamber by movement along the N. 30° E. shears in and adjacent to the intrusive indicates that the magma

was forcibly injected into the schists. In the early stage of intrusion of the stock, prior to the faulting along N. 30° E. shears, *lit-par-lit* injection of a leucocratic phase (granodiorite) of the quartz diorite magma into the schists may have aided in the enlargement of the chamber. An upbowing or doming of the schists along the northeast contact and a pushing aside, on the southwest margin, may have been caused by the push of the magma.

Form of the quartz diorite intrusive.—The intrusive at the levels exposed is a subcircular stock whose axis plunges about 55°–60° NE. If one were to project the intrusive contacts on the basis of orientation of the structures in schist and intrusive, the quartz diorite mass would taper upwards with a northeastern contact dipping 50° NE., and the northwestern, southwestern, and southern contacts would dip more steeply toward the center of the stock. At depth the body may continue to parallel the trend of the schists (Fig. 6), or it may be more restricted to a N. 30° E. shear (Fig. 5).

Such projections should be used with caution. Flow layers near the margin would not reflect a sudden change in the direction of the contact a few hundred feet distant. However, such a change would probably be reflected in the layers farther from the margin.

THE ORE-BEARING STRUCTURES

GENERAL DISCUSSION

The ore deposits occupy faults and zones of close jointing on the arch of flow layers. Veins lie transverse to the axis, but the ore-bearing zone extends along the axis. The structures were formed by movements, individually of small magnitude, acting on pre-existing joint planes. The persistency and frequency of these joints, as discussed, is apparently determined by their relation to the arch of flow layers. The forces which caused the movements were probably directly related to the intrusion of the quartz diorite stock. Structures developed by regional stresses controlled the emplacement of the stock, but it is not known if such stresses were present during intrusion.

The outstanding feature of the ore-bearing structures is their control by primary flow and fracture patterns. There are two main structural types of ore deposit: (a) those occupying well-defined fissures (faults), and (b) those in zones of close jointing. All gradations between these two types occur. The former are the more persistent; the latter, though of limited extent laterally and vertically, often contain higher-grade ore.

North of H vein (Pl. 2) the veins are of type (a). Here the flow layers are strongly developed on the axis of the arch. Where the diagonal joints (types 4, 5) parallel the plane of the flow layers, joints of these orientations are common and persistent. Faults, or fissures, have formed along the plane of the flow layers and primary joints. These structures are strong where they develop parallel to the flow layers on the axis of the structure but die out on the flanks where they transect the flow layers. Several fissures curve slightly in concordance with the curve of the flow layers on the flanks before pinching out.

South of H vein many of the veins are of type (b). The flow layers are poorly developed along the axis but strong on the flanks. Movement has been chiefly along the sets of close diagonal joints (types 4, 5). Ore-bearing structures may roll from one set to the other. With the exception of B vein the displacement has been small, generally insufficient to offset the cross joints (type 3). The persistent southwest-dipping cross joints (type 3) form the roofs of many of the ore shoots.

B vein occupies a shear zone in which the quartz diorite has been in part mylonitized. Movement has offset the cross joints at least 7 feet. A depression lies on the continuation of B vein to the southwest. It is probably underlain by a strong shear of the N. 30° E. type. It is significant that no worth-while deposits have been found south of B vein.

In addition to those on the axis of the arch other veins occur, but here too the control by flow layers is apparent. At Edye Pass Mine, D5 vein occupies a persistent fault, paralleling the flow layers, and joints of type 5, on the limb of the arch. D3 vein lies in one of the strong N. 30° E. shears. This shear zone of highly mylonitized rock is over 6 feet in width. It continues across schist and intrusive regardless of orientation of flow structures; nevertheless, quartz-pyrite lenses occur in this structure where the shear parallels the flow layers. Veins near the mouth of Little Useless Creek also parallel the flow layers; one of these veins lies transverse to a minor arch of flow layers.

It is difficult to measure displacements on the ore-bearing structures. The data obtained indicate movements that resulted in a northeasterly lenthening of the intrusive, in the area of the arch of flow layers (Fig. 3). This lengthening nearly paralleled the axial plane of the arch and the trend of the lineation. The slickensides all plunge at low angles. Such movements would tend to widen the channelways for the ore-bearing solutions.

ORIGIN OF THE N. 30° E. SHEARS

Inasmuch as the ore-bearing structures and the N. 30° E. shears probably resulted from the same stresses, a short discussion of these shears is pertinent at this point.

Although N. 30° E. joints (type 1) are common in the area, only within a mile of the intrusive are shears of this orientation conspicuous. Three of these shears lie west of the intrusive. D3 (Pl. 1) shear cuts both intrusive and schist. These four structures are remarkably straight and persistent; they can be readily traced as draws on the surface. A similar draw continues southwest from B vein. In the eastern part of the stock the parallelism of the southern portion of the three forks of Little Useless Creek suggests structural control of the drainage by similar fractures.

Faulting along these shears followed solidification of the quartz diorite, at the levels now exposed, and preceded ore deposition. Although these faults do not bear the same relationship to the contacts of the intrusive as do the gently dipping marginal thrusts and normal faults described by Balk (1937, p. 101–111), nevertheless they may have served the same purpose—namely, to lengthen an expanding intrusive, already solidified at its margins.

Contacts and slickensides on D3 shear suggest that the southeast side of the fault moved almost horizontally northeastward in a manner to be expected if the intrusive was expanding by pushing northeasterly.

ORIGIN OF THE ORE-BEARING FRACTURES

The ore-bearing fractures probably were formed by the same stresses as the N. 30° E. shears, but in this case relief was not by a long-continuous fault but by a series of much smaller movements involving the joint planes already developed on on the axis of the arch of flow layers. The effect however was the same—namely, to facilitate expansion of the magma chamber to the northeast.

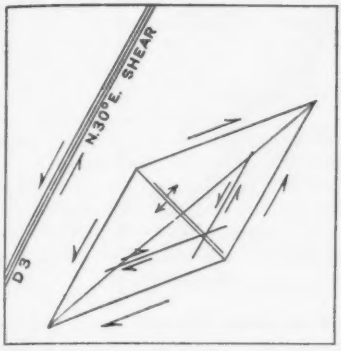

FIGURE 8.—*Effect of shear in northwest portion of stock*

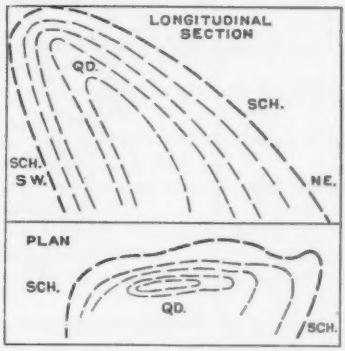

FIGURE 9.—*Reconstruction of arch of flow layers*

The easiest relief to the stresses was apparently by movement embracing the transverse joint planes rather than by the formation of a through-going shear along the axis. That the stresses were the same is indicated by the presence of a northeast-trending shear south of B vein.

The elongation to the northeastward would not be a simple dilation in that direction. In the area of D3 and the axis of flow layers the maximum northeastward movement occurred to the southeast. A shearing stress would exist in the area (Fig. 8). The effects of such a rotational stress are discussed by Mead (1920). Relief to this stress was by faulting along D3 shear and by the smaller movements along the axis. The direction of maximum elongation in this rotational stress would be northeast.

The action of this shearing stress on the northwest portion of the intrusive explains the nearly horizontal slickensides on the joints and ore-bearing fractures (Figs. 3, 8). If this couple were effective during the earlier stages of the intrusion it may have caused the progressive eastward rotation (Figs. 4, 8) of succeeding primary structures: axis of flow layers, flow lines, and the normal to the cross joints.

EXTENSION OF THE ORE ZONE

Since structural control of the deposits was established by mapping internal structures in the intrusive, it is of interest to see what predictions can be made as to the probable lateral and vertical extent of the deposits.

The veins were formerly considered to occupy tension cracks of limited vertical

range (200–300 feet) formed by cooling near the roof of the intrusive. Reconstruction of the form of the intrusive, using the flow structures, platy and linear, and the trend of the schists, indicates that veins of Surf Point Mine lie about 1000 feet below the roof of the stock. Hence a much greater vertical range for the ore zone is suggested for the deposits.

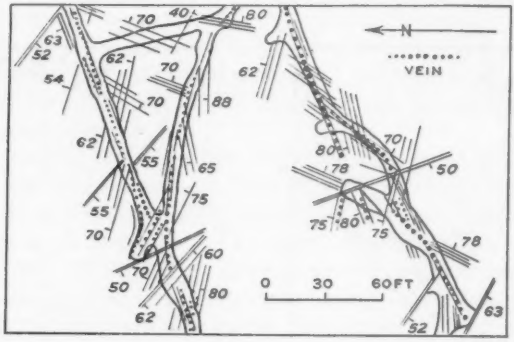

FIGURE 10.—*Effect of jointing on ore-bearing structures*

The lateral extent of the zone is limited by the arch of flow layers. At depth the deposits should continue to occur along the axis of the arch—*i.e.* in a zone striking N. 20° E. and dipping 80° SE. Within this zone the maximum concentration of ore occurs at present levels between H and B veins. Whether this results from the change in the character of the intrusive and vein structure, or from an increase in the strength of ore-bearing structures on approaching the shear south of B vein, is not known. In either case the maximum concentration within the ore zone should rake steeply to the northeast.

SUMMARY AND CONCLUSIONS

The quartz diorite stock in which the ore deposits occur was forcibly injected into older schists. The planes of easy parting in the schists, schistosity and tension joints controlled the outlines of the intrusive. In the stock an arch of flow layers formed early. The succeeding linear structures had a constant trend. Primary joints had fixed orientations, but their persistency, frequency, and location were controlled by the arch of flow layers. The intrusive expanded partly by movement along N. 30° E. shears and partly by movements involving the joints already developed along the axis of flow layers.

The sequence—flow layers, flow lines, primary joints, ore-bearing structures—is directly related to the mechanics of the intrusion. The ore-bearing solutions probably came in shortly after the development of these structures and originated as an end product of the consolidation of the magma at depth.

Mapping the internal structures of intrusives in which lode deposits occur may yield guides to prospecting and development. The application of Cloos' methods

may give valuable information on such practical considerations as the form of the intrusive, the order of depth of known deposits below the contact, an estimation of the vertical range of the deposits, the strike, dip, and rake of the ore-bearing zone, and may indicate favorable and unfavorable areas for prospecting or exploration.

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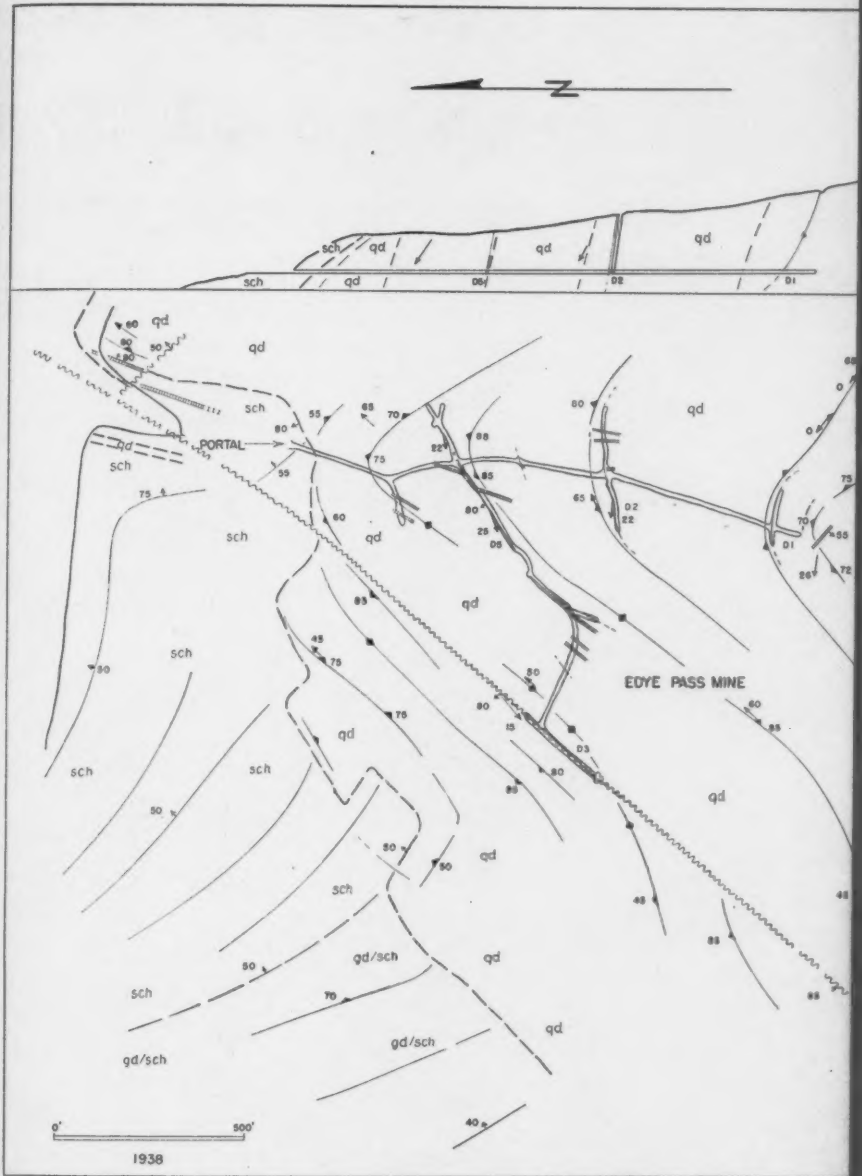

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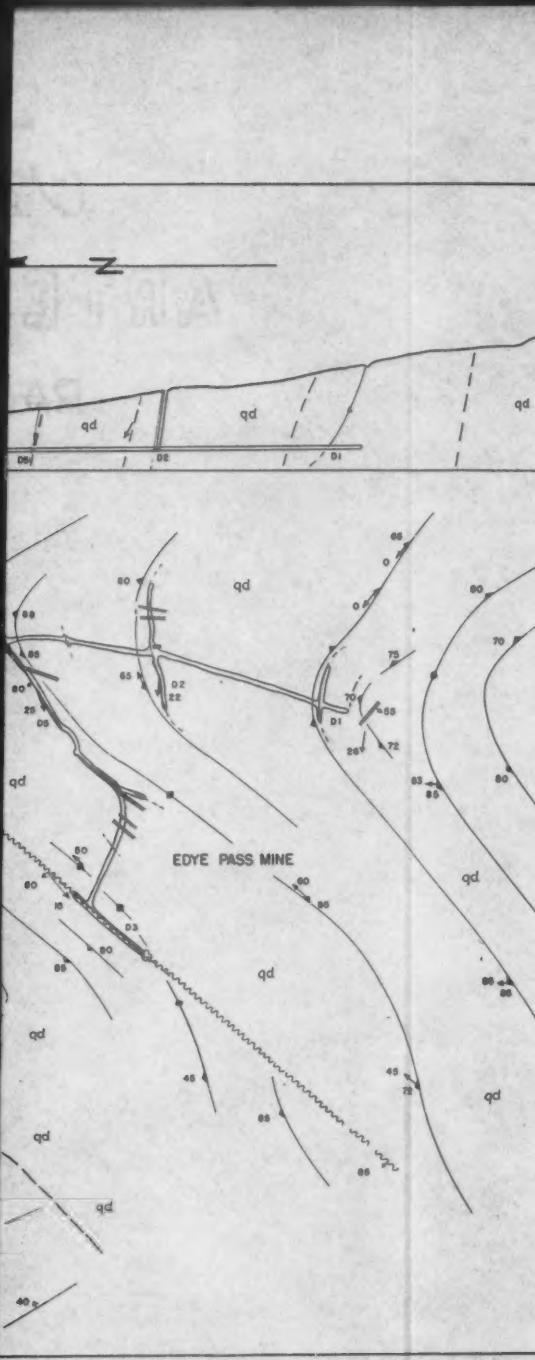

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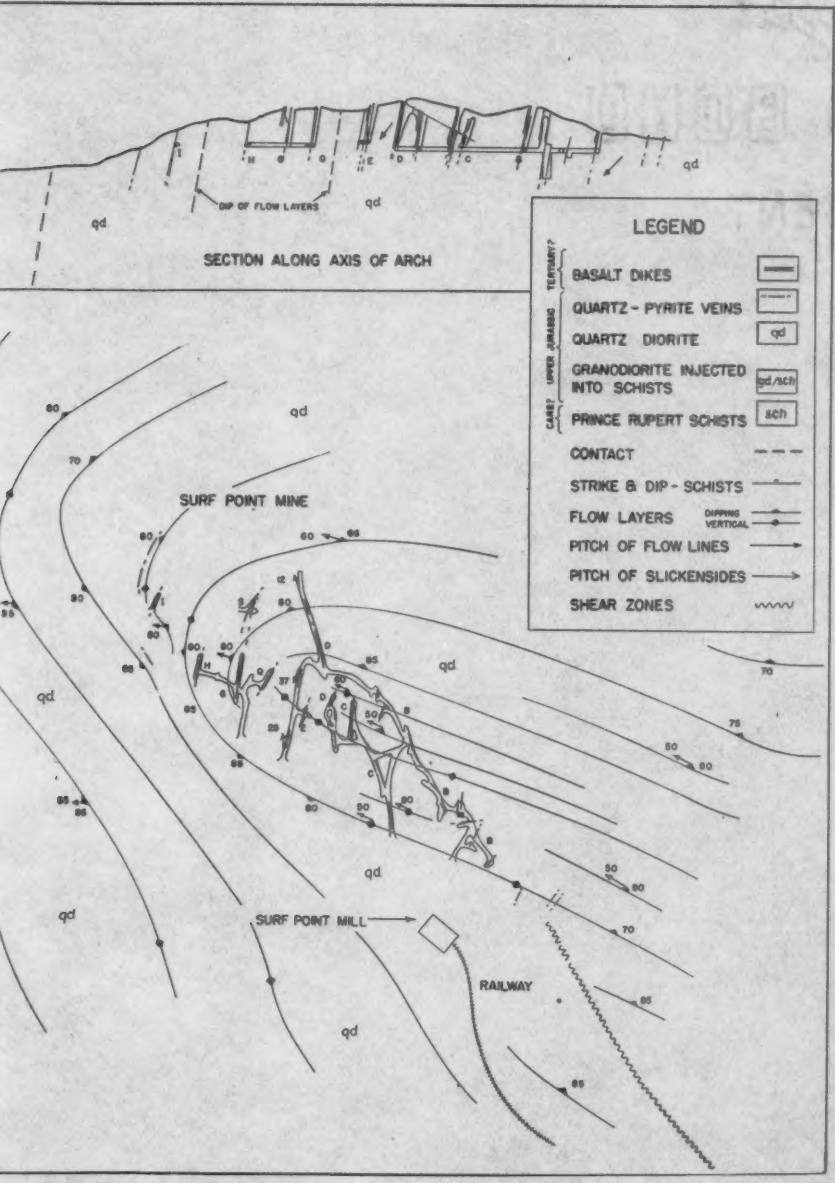

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